



### **ESIN AND ERDOGAN GULARI**

*of Wayne State and  
Michigan*



Tray Drying of Solids  
AFACAN, MASLIYAH

Dimensionless Education  
ANDREWS

Teaching Professional Ethics  
WOODS

The Thermodynamics of Exergy  
DEBENEDETTI

Thermal Conductivity of a Hotdog  
MATTESON, SOMMERFELD

Kinetics and Catalysis Demonstrations  
FALCONER, BRITTEN

How We Make Mass Transfer Seem Difficult  
CUSSLER

Process Design in Process Control Education  
KARIM

Microcomputer Based Laboratory for Teaching Process Control  
JOSEPH, ELLIOTT

Two Lost-Work Statements and the Combined First- and Second-Law Statement  
DE NEVERS, SEADER

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# *Esin and Erdogan Gulari*

*of Wayne State and Michigan*

**"Keeping all the balls in the air"**

H. S. FOGLER

*University of Michigan  
Ann Arbor, MI 48109*

R. H. KUMMLER

*Wayne State University  
Detroit, MI 48202*

Dual-career families are becoming commonplace, but the effort required to succeed on all fronts is enormous. Careers as researchers and tenured professors of chemical engineering mean complicated logistics for Esin and Erdogan Gulari in the planning of their daily routine.

For Esin, it means getting up at 6 a.m. to drive the 45 miles from Ann Arbor to Detroit to teach her morning undergraduate class at Wayne State University, returning after teaching her evening graduate class.

For Erdogan, it means preparing their son Bora's breakfast and getting him off to school before going to The University of Michigan to teach his morning class and meet with graduate students.

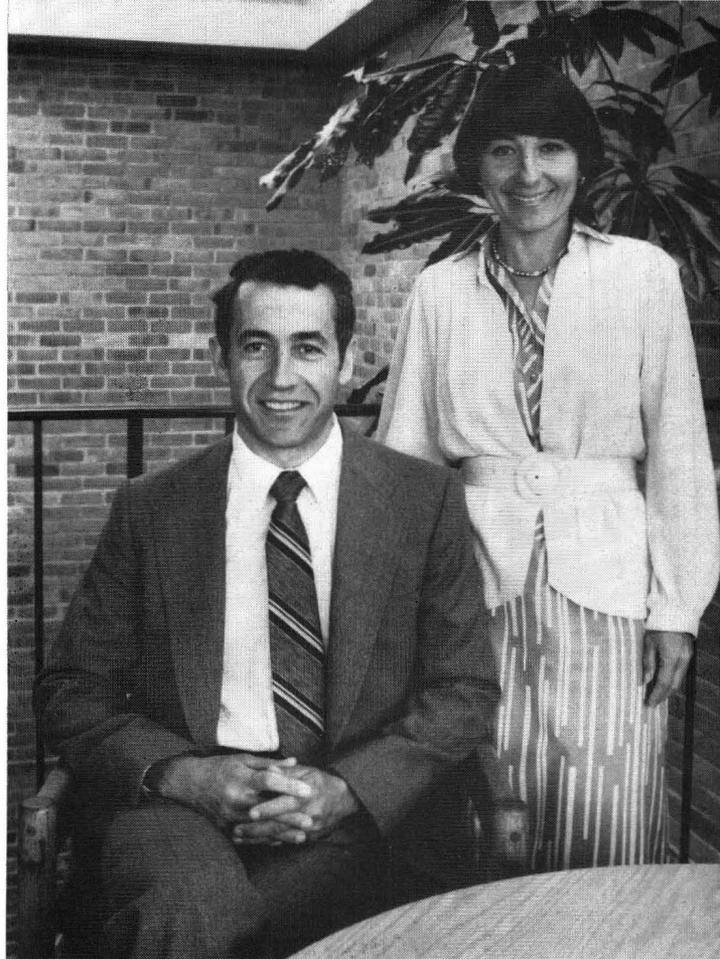
For both of them it means making sacrifices and juggling schedules and setting priorities. But the Gularis want it all and are willing to work at it.

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**[Esin's] interest in transport and physical properties of fluids make her one of WSU's leading instructors in transport phenomena, unit operations, and thermodynamics.**

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Two outstanding careers in chemical engineering are at least partial evidence that their hard work has paid off.

They received their B.S. degrees in chemical engineering in 1969 from Robert College in Istanbul, Turkey, and were married the following summer. In the fall they began graduate school at Caltech, both choosing Professor Neil Pings as thesis adviser. After receiving their Ph.D. degrees in 1973, Erdogan accepted a postdoctoral fellowship with Professor Ben Chu at the State University of New York at Stony Brook while Esin combined teaching of physical chemistry with research under Professor Chu's direction.

In 1974 the Gularis returned to Turkey, where they accepted positions as Laboratory Manager and Technical Manager of a large vegetable-oil extraction plant along the Aegean coast. They were responsible for the design and construction of a coal- and oil-fired power plant, and were also in charge of the technical operation, which included extraction and refining plants, product control and improvement. Of the experience, Erdogan says, "It taught me how to deal with and manage people. It was an interesting change from being a postdoc to holding a position of responsibility for many people."

But the small town was isolating intellectually,

and when plant construction was finished and start-up problems solved, management of the routine operation did not provide sufficient challenge. So they gave up secure jobs in Turkey in search of positions involving teaching and research in the U.S.

Esin and Erdogan returned to the academic environment at SUNY-Stony Brook and resumed postdoctoral work with Professor Chu in the area of laser lightscattering. In 1978 Erdogan accepted an offer to join the faculty at The University of Michigan. During their first year in Ann Arbor, Esin taught chemistry at nearby Eastern Michigan University. In the spring of 1979 she joined the chemical engineering department at Wayne State University.

### ESIN GOES TO WSU

The legend of Esin Gulari at WSU began with an incident that has become an infamous story. During her second interview, just as the faculty had determined that Esin was indeed the scholar and teacher they wanted and were busy convincing her that WSU was the place for her, her car was towed away by the Parking Authority. Was this a warning about the Big City Campus or a sign that WSU would not let her go?

In an incredibly short time Esin has created a laser lightscattering laboratory and built a student research group of a half dozen students actively pursuing research projects. Her students are also welcome in Erdogan's Ann Arbor laboratory whenever additional equipment is necessary.

At Stony Brook, Esin, jointly with Erdogan, developed an inversion technique to evaluate particle size distributions of colloids and polymers from dynamic light scattering data. Her research at WSU now centers on using lasers, "a nonintrusive and precise probe," to study fluctuations in fluids.

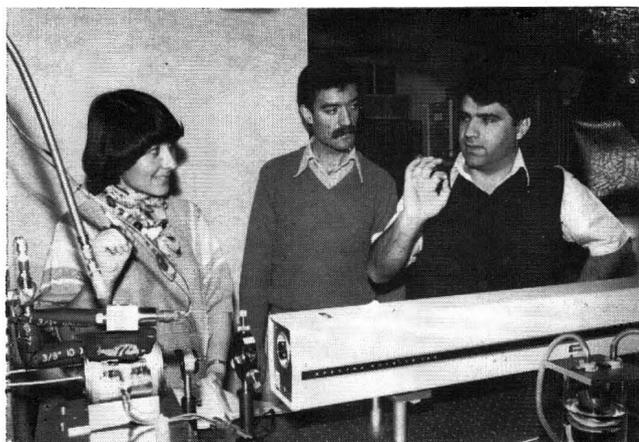
A major focus of her research concerns the diffusion of compressed gases in liquids and medium molecular weight hydrocarbons in dense gases with urgent interest because of the use of  $\text{CO}_2$  as a miscible solvent in tertiary-oil recovery and supercritical extraction processes. Esin has been able to use photon correlation spectroscopy to measure the binary diffusion coefficient at elevated temperatures and pressures in these systems. Her group introduced the use of a "probe particle" of known radius for measuring liquid viscosities.

Most recently, she has been concerned with the physical properties of polymeric emulsions. The

average molecular weight and the molecular weight distributions determine the principal physical properties, and hence it is crucial to be able to predict and control the polydispersity of a polymer. Understanding the mechanism of initiation is an important goal of Esin's research. She has demonstrated the existence of at least two competing mechanisms in the polymerization of styrene in microemulsions.

Future research efforts for Esin's group will involve the use of a unique detection scheme of diffraction patterns to characterize diesel sprays.

Esin brings simultaneous dedication to teaching and research. Moreover, she brings enthusiasm and personal qualities which motivate those around her. Members of the WSU faculty who appreciate her sense of humor are in awe of the tough taskmaster image she maintains with her students. She teaches with equal ease at the



**Esin and students discuss their latest problem.**

undergraduate and graduate levels and has introduced a special graduate course in optical spectroscopy in chemical engineering research. Her interest in transport and physical properties of fluids make her one of WSU's leading instructors in transport phenomena, unit operations, and thermodynamics.

It is obvious that both Esin and her students enjoy their work. Much of her time is dedicated to one-on-one instruction. Even the casual observer cannot help but notice the many hours that graduate students spend in her office and laboratory and their total involvement in her research projects.

Industry recognizes the excellent results Esin achieves. Her students are in demand, and she has a steady stream of visitors examining her laboratory so that they can emulate the equipment. She consults for industry in the Detroit area and also

has visited laboratories in Ludwigshafen, Germany, in collaborative efforts.

There is another facet of Esin's career: service to AIChE. She has served as director, secretary, and was recently elected as vice chairman of the Detroit Section. During her tenure, the Detroit Section has enjoyed some of its most successful years, culminating with the outstanding local Diamond Jubilee Program last year.

### ERDOGAN SETTLES IN AT MICHIGAN

For Erdogan, research is not only a scholarly challenge, it's fun. As his graduate students say, coming to the lab "is like coming to play. A new project or a new piece of equipment is like a new toy to him." His enthusiasm is contagious, and his students enjoy their work. Actually, they say, he is as excited about their successes as he is about his own, and he often spends extra hours in the lab sharing their highs (or lows).

Erdogan is happiest tackling new problems rather than doing what somebody else has already done or is currently doing. "Don't reinvent the wheel," and "an hour in the library is worth ten in the lab," he tells his students. His interest in new frontiers led him to research in periodic and unsteady state operation of catalytic reactors.

Erdogan's two most significant research accomplishments have been: the establishment of

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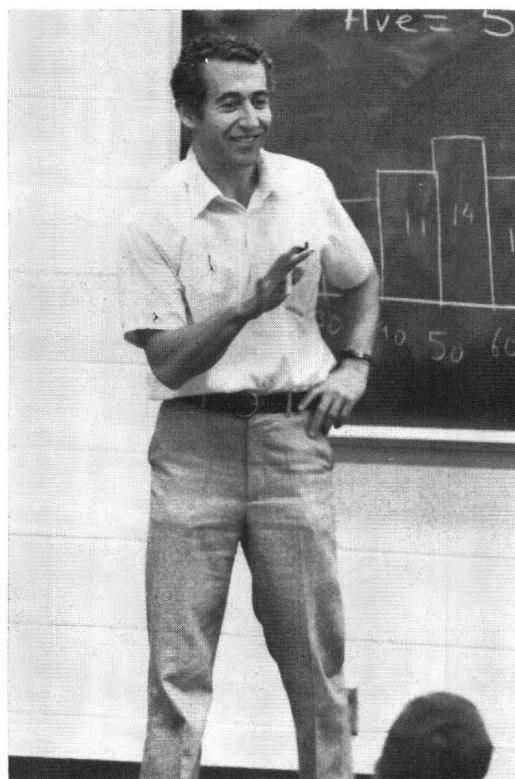
**[Erdogan] is working on unsteady state operation of catalytic reactors and has developed a reactor system that allows investigation of transient phenomena in the millisecond time range.**

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dynamic lightscattering as a reliable means of measuring the mutual diffusion coefficient and thermal diffusivity; and with Esin, the development of an indirect inversion technique to evaluate the Fredholm integral of the first kind in order to obtain particle size distributions from dynamic lightscattering data.

He is currently working on unsteady state operation of catalytic reactors and has developed a reactor system that allows investigation of transient phenomena in the millisecond time range.

Erdogan's work in adsorption of sulfonate based surfactants on germanium oxide was the first molecular investigation of surfactant adsorption which clearly demonstrated which functional group was responsible for adsorption, and it showed that the hemimicelle theory of adsorption



**Not a conventional teacher, Erdogan enjoys the challenge of the classroom.**

was not in agreement with the molecular picture of adsorption.

In order to carry out his research Erdogan first had to build his laboratory—almost from scratch. He has built a spectroscopy lab matched by few across the country, and other investigators now send both their students and their samples for testing to his lab.

Part of the challenge of research is in teaching research. He expects and encourages his students to do their own thinking and experimentation. According to his graduate students, "If you come up with a good idea, you are encouraged to try it out. He is very open-minded and almost never imposes his own way of doing things. He would rather have you try and fail than not try at all."

He believes in students' independence in the laboratory and in the classroom. For that reason Erdogan would not be described as a "conventional" teacher. He often leaves holes for students to fill in on their own, inviting thought and investigation rather than providing every detail for them. But he is very willing to spend time with individuals when they request additional information or guidance.

"One of the rules I try to follow in teaching is to make sure that the students understand

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**On local waters . . . Professors Gulari are known as Bora's mom and dad. When he was six years old, weighing only 43 pounds, Bora was the youngest windsurfer in the world. He won the championship in the Ann Arbor "B" fleet competition over nine other contenders when he was only seven years old.**

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that I am there to help and encourage them in their learning process, both on a one-to-one basis and also in the classroom, and that I care about them." In order to better interact with the students, he divides his large classes into small discussion groups where problems can be discussed informally. "My emphasis in these discussion sessions is not just to solve problems or answer questions, but also to get the students to think and arrive at the answer, starting with the most fundamental definitions or equations."

"To me, teaching is more than a requirement of the job. I do not agree with the claim that good researchers make poor teachers." Erdogan is determined to get the material across, even to the largest classes, and he will try new approaches when old ones fail.

#### **FAMILY ACTIVITIES WATER-ORIENTED**

Busy teaching and research schedules for husband and wife leave little spare time for the Gulari family. As much time as possible, though, is spent on one of the nearby lakes or rivers. The Gularis are avid sailors. They started sailing as a means of relaxation while writing their theses at Caltech, and Bora tasted the salty spray of the Mediterranean when he was only three months old.

A tribute to Erdogan's sailing abilities came in the fall of 1983 when he was sponsored by the sailboat manufacturer Banshee in the national championships in Alameda, California. He finished second in 1982 and fifth in 1983 in this single-handed mono-hull class.

Recently the Gularis' interests have turned to windsurfing. "I love the freedom and independence windsurfing offers," says Esin. "After work, on a day when the westerly blows, it is very refreshing to feel the board take off and literally fly for an hour." "I especially like to sail in stormy weather," says Erdogan. "While physically demanding, it provides total mental relaxation."

On local waters around Ann Arbor, Professors Gulari are known as Bora's mom and dad. When he was six years old, weighing only 43 pounds, Bora was the youngest windsurfer in the world. He now beats many adults, even on windy days. He won the championship in the Ann Arbor "B" fleet competition over nine other contenders when he

was only seven years old. He has appeared on television news shows, and many regional newspapers have carried articles and photographs. At the age of 8, Bora Gulari has developed into a "big-shot" windsurfer.

Collaboration, yet independence, seems to be a key to the mutual success of the Gularis. They shared the expertise of common dissertation and postdoctoral advisers and have co-authored a



**Bora, a champion windsurfer, displays his skill.**

number of papers. Sharing the same initials, though, has led to occasional mixups, with Erdogan getting credit for Esin's papers. To minimize the problem and to clearly show their independence in research, they have made special efforts not to work on closely related problems and have not co-authored any papers for the last six years.

Both The University of Michigan and Wayne State University are proud of the professional relationship the two Professors Gulari have fostered between the schools. Chemical engineering in the State of Michigan certainly benefits from this unique sharing of knowledge and ideas. □

*Note: The authors would like to acknowledge Valerie Franklin for her invaluable assistance in preparing this article.*



General view of Quadrangle 2 of Syracuse University with domed stadium for 50,000 people on the left.

**ChE** department

## ***SYRACUSE UNIVERSITY***

ALLEN J. BARDUHN AND  
LAWRENCE L. TAVLARIDES  
*Syracuse University*  
*Syracuse, NY 13210*

**O**UR CHEMICAL ENGINEERING department is an important part of the L. C. Smith College of Engineering, which is named after the famous Smith of typewriter fame who was born and raised in the area of Syracuse. The college is one of eleven at Syracuse University which has 11,000 undergraduate and 4,000 graduate students from all fifty states and ninety-four foreign countries. A mosque, a synagogue, and several churches (orthodox, catholic and protestant) are all within a short walking distance of the S.U. campus.

The university began its first academic year in 1871 and was established as a residential uni-

versity by the Methodist Church, but it has since become nonsectarian. There are enough residential facilities (dormitories, fraternities, sororities, and individual apartments) on or near campus to house the entire student body (and their families, in the case of graduate students).

We take pride in our university as well as our department. In 1966 the university was elected to the prestigious American Association of Universities (AAU), to which belong only fifty-two of the better known universities in the nation, including all the Ivy League institutions.

The department and Syracuse University as a whole are currently engaged in a new enterprise: the Center for Advanced Technology in Computer Applications and Software Engineering (CASE Center). Formally designated by the governor in February, 1984, the CASE Center is one of seven New York State Centers for Advanced Technology. It is a particularly promising example of the current national trend toward increased interaction between universities and industry. Building upon Syracuse University's longstanding ties with industry, the Center is helping to improve the University's research facilities, to strengthen academic programs, and to support economic growth in New York. Current projects conducted

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**The department and Syracuse University as a whole are currently engaged in a new enterprise: the Center for Advanced Technology in Computer Applications and Software Engineering (CASE Center).**

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through the Center by chemical engineering faculty members include investigation of electromigration in thin film microconductors, development of knowledge-base on properties of materials, and work on computer software for finite-element analysis in chemical separation theory.

Our campus of two hundred acres is well maintained and has the only domed stadium in the state of New York. A recent visitor to our department (a seminar speaker) said, "This campus looks just like a university campus ought to look!" The campus is adjacent to the State University of New York (SUNY) College of Environmental Science and Forestry, which has a first-class chemistry department. All S.U. students may take courses there.

Syracuse University has always emphasized the sports of football and basketball, and some of us professors used to view this practice with disdain. But right after 1959, when S.U. won the national championship in football, we got the largest and best crop of chemical engineers we had ever seen. Since then we don't disdain our superiority (some years) in sports.

The city of Syracuse was named after the Greek city-state of the same name, now in Sicily. It was in the old Syracuse that Archimedes shouted in his bathtub, "Eureka!" when he discovered the principle of buoyancy 2200 years ago. We always mention this in Transport I (fluid mechanics). The mayors of Syracuse, New York, and Syracuse, Sicily, frequently visit each other in current times.

Syracuse is in the center of New York state and has excellent air transportation since it is served by four major airlines and six feeder lines. The city is near the beautiful and largest state park in the nation, Adirondack State Park. It is an industrial city that is host to many diversified industries which include Allied Corporation (Chemical Sector), important divisions of General Electric, General Motors and Bristol-Myers; Millers and Matts Breweries, and a host of other companies making ball bearings, electroplated items, specialty steels, etc. Syracuse is also the headquarters of the Carrier Corp., the first and original air-conditioning company in the world, and of Crouse-Hinds the manufacturer of electrical components and of the first commercial red and green traffic signals in about 1920.

## THE DEPARTMENT

Our department was originally a part of the Chemistry Department and we awarded our first

BS in chemical engineering in 1917, our first MS in 1922, and our first PhD in 1949. We separated from chemistry and became part of the Engineering College as the Department of Chemical Engineering and Metallurgy in 1914, but our title was changed in 1973 to Chemical Engineering and Materials Science.

Our department chairman before 1954 was Charles D. Luke, who left to take a job with the government. The next chairman was James A. Luker, and when he became Dean of Engineering we began looking for another chairman. Then some wag suggested we look for a chairman named



**Hinds Hall, home of chemical engineering and civil engineering.**

Lukest so that we would have the procession of Luke, Luker, Lukest!

Some notable BS graduates have been Andreas Acrivos (1950), now teaching at Stanford, the late Leon Lapidus (1945), formerly a professor and department head at Princeton, and Donald G. Stevens, former Vice President of SOHIO.

The department presently consists of fourteen full time faculty, including three professors of materials science and eleven professors of chemical engineering. A fifteenth has full time administrative duties as Vice President for Research and Graduate Affairs of S.U. There are 104 undergraduate students, 43 graduate students, 9 post doctoral research associates, and 3 visiting scholars. The department presently occupies 27,000 square feet of space in Hinds Hall and Link Hall, exclusive of classrooms.

## THE UNDERGRADUATE PROGRAM

One of the outstanding features of our undergraduate program is the individual attention we give our students. The present (1984) student-to-

faculty ratio is less than fifteen. This structure gives us the opportunity to interact closely with the students so that we can instill a sense of pride in their engineering and scientific accomplishments and a high level of confidence in their background. All of the eleven faculty members in chemical engineering are involved in undergraduate teaching.

Another characteristic of our program is the participation of undergraduate students in research projects. This year over twenty percent of the seniors and some juniors are performing research under the guidance of the faculty. Some seniors have had articles accepted for publication in technical journals prior to graduation and have given presentations at national AIChE meetings.

The undergraduate curriculum is a typical blend of mathematics, physical sciences, and engineering courses. Most of our students follow the General Chemical Engineering Option which covers the traditional program terminating in the senior courses in process design and control. By replacing certain upper level courses in the general option, students can tailor their program of study to the options in environmental systems or materials science. For the former option, courses in biology, air pollution, and waste treatment are added, while courses in the structure and properties of materials, polymer science and processing, and metallurgy can be added in the latter option.

A few years ago, a freshman chemical engineering computing course was instituted, and this year it is being taught in our new microcomputer laboratory. All of the courses (especially those in design and control) are being updated to reflect the growing importance of computers in the engineering profession. It is also useful to get the freshman students into chemical engineering courses before their sophomore year. We are pleased to report that renovation of the undergraduate laboratory will begin this summer. In addition to moving to a new location with more space, modern instrumentation (including microcomputers for data acquisition and analysis) and new experiments in materials properties and processing are being installed, with funds provided by the IBM Foundation.

## GRADUATE EDUCATION AND RESEARCH

The Department of Chemical Engineering and Materials Science offers a MS and a PhD in chemical engineering. Masters candidates may pursue the thesis or non-thesis option, although all

students on research or teaching assistantships must complete a master's thesis. The thesis is 6 semester hours of the 30 semester hour total. The PhD requires 90 semester hours beyond the BS of which up to 39 hours may be doctoral dissertation. Presently there are 43 full-time Chemical Engineering and Materials Science graduate students in the department, 40 percent of whom are PhD candidates.

Considering the size of the department, research covers a broad spectrum that includes biomedical, catalysis, surface science, materials science, polymers, electrochemistry, process simulation and control, separation and transport processes.

For the twenty-three years prior to 1980, **Allen J. Barduhn** did a lot of research on desalting sea water by freezing and by gas hydrate formation and became an expert on the growth rates of ice crystals and the thermodynamics of many gas hydrate systems. In 1964 Barduhn invented the eutectic freezing process for treating waste waters.

**John C. Heydweiller** is investigating the optimal design of entire processes by using the Rayleigh-Ritz approach to incorporate distributed models. This project involves the investigation of various approximating functions and search procedures to find an efficient and robust combination. Another topic of interest to Heydweiller is the numerical solution of partial differential equations, particularly those involving steep fronts.

**Vasilios A. Karagounis** is interested in the photolithographic fabrication of dissolved oxygen and pH sensors on silicon chips. Theory is developed for unsteady state measurements of oxygen concentration using cyclic voltometry at high scan rates. He is also investigating the adhesion of metals on polymer substrates. This study concentrates on the development of plasma treatments of substrates which will increase the number of covalent chemical bonds at the metal-polymer interface. The scanning electron microscope (SEM), electron spectroscopy for chemical analysis (ESCA), and Auger spectroscopy are used to examine the interface.

Mathematical models for insulin and glucose metabolism in humans are also being developed by Karagounis. Simulation studies, using the Advanced Continuous Simulation Language (ACSL), explore the effectiveness of different control schemes (feedback, feedforward, adaptive and inferential) in controlling glucose in diabetic patients with an artificial pancreas.

**Hao-wen Liu**, in materials science, is studying cyclic loading at elevated temperatures which reduces service lives of engineering structures and engineering components. Oxidation, particularly grain boundary oxidation, is being investigated as the damaging mechanism for the reduced service lives. Also, the slip systems associated with crack growth and the applied stresses on these slip systems are being studied. The characteristics of crack tip deformation in large scale yielding and in general yielding are being analyzed and the results of the crack tip field analyses are being used to study elastic-plastic fracture mechanics and crack growth in strain controlled fatigue.

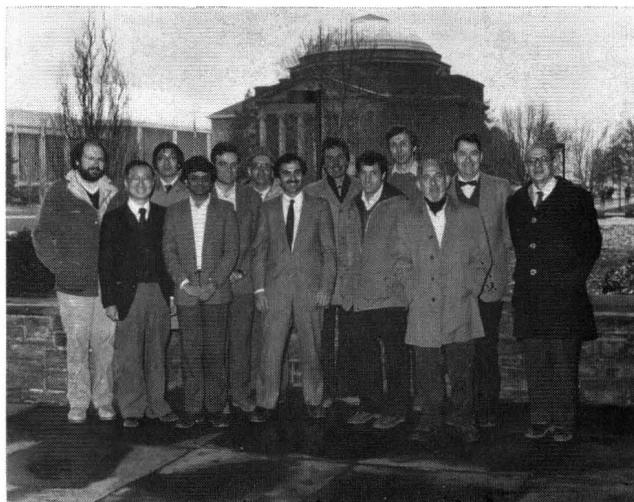
Using a cyclic mechanical load, cyclic slip will take place in crystalline materials. Fatigue damage is closely related to the changes in dislocation structure caused by cyclic slip and the resulting crystal distortion, which is measured with x-ray diffraction. The results of this study enable us to monitor fatigue damage in materials and engineering structures.

The relationship between the molecular structure of the polymer chain and the physical behavior and performance of the material is being investigated by **George C. Martin**. His primary interest is in the physical properties and applications of polymers. He is investigating the use of polymer elastomers as integral components in micro-electronic and micro-optical devices. He is interested in the rheology and characterization of polymer composites, especially with respect to the nature of the curing process, the glass transition temperature, and the mechanical performance and processing of the materials.

**P. A. Rice** recently completed an investigation of the stripping of emulsified refrigerant from water in a vacuum spray chamber. This work shows that the major mechanism for the removal of emulsified refrigerant is the flashing of the droplets as they are exposed to the chamber atmosphere when the surface of the disintegrating liquid sheet expands. Rice is also pursuing an interesting joint project with Upstate Medical Center on the effect of ethanol on the rate of amino acid transport in the human placenta.

**Ashok S. Sangani** is studying the fluid mechanics and stability of magnetic fluids or suspensions of magnetized solids. Such phenomena are important in leakproof seals and magnetic ink jet printers. The development of theoretical models for prediction of the effective transport properties of two phase media is another research interest of Sangani.

**Klaus Schröder** is presently interested in magnetic properties of fine particles and thin films. He is studying the effect of ultrasonic stress waves on magnetization changes. The materials used in these investigations are BiMn alloys with small



**Faculty of Chemical Engineering and Materials Science. Front Row left to right: Liu, Sangani, Tavlarides, Heydweiller, Barduhn, Stern. Second Row left to right: Martin, Tien, Karagounis, Schroder, Schwarz, Rice, Vook. Missing are C-S Wang (on leave) and V. Weiss, who is a Vice President of S.U.**

ferromagnetic BiMn precipitates, and MgO with magnesioferrite precipitates. Schröder is also measuring the effect of a non-magnetic overlayer on the magnetization of thin iron and nickel films.

**James A. Schwarz** is our specialist in catalysis and is investigating adsorption-desorption kinetics of reactive gases important in the production of synthetic fuels and is developing novel methods of analyzing surface reactions using cyclic operations. He has recently extended his interests in surface chemistry to the area of micro-electronic device-fabrication and reliability.

**S. Alexander Stern** is studying the separation of gaseous and liquid mixtures by selective permeation through polymer membranes. In the area of gas separation, the studies are concerned with the mathematical modelling of new concepts of membrane process design, such as recycle and multimembrane permeators. The results of these studies are being tested experimentally. The separation of azeotropic mixtures by pervaporation, osmotic distillation, and osmotic phase separation is also being studied theoretically and experimentally. The main research effort is being de-

Continued on page 152.

## TEACHING PROFESSIONAL ETHICS\*

DONALD R. WOODS  
*McMaster University*  
*Hamilton, Ontario, Canada L8S 4L7*

We expect all of our graduates to "behave as professionals." One characteristic is that professionals are ethical. This simple statement has four interesting components

- **Personal ethics:** individuals have their own internal ideas of right and wrong that they may or may not be aware of.
- **Professional ethics:** our engineering profession (as national organizations and as state or provincial associations) have published codes of ethics which they expect all professionals to use as their value system.
- **Microethics:** some value decisions involve us as individuals being ethical in our professional context.
- **Macroethics:** some value decisions involve ensuring that our company or institution behaves ethically.

What types of learning experiences can be used in the classroom to sensitize our students to this important professional attitude, and what resources are available?

### BACKGROUND EXPERIENCES

If students have difficulty identifying their own ethics, then some techniques on values classification could be used. Some resources include Barrs et al [1] and Larson et al [2]. In these experiences, students learn to express their personal values. So far in our program, we have not used this as an introduction.

### CODES OF ETHICS AND RESOURCES

A unified code [3], the AIChE code [4], and various state or provincial codes [5] are available. Some are more explicit than others and help guide

\*Paper presented at the AIChE Annual Meeting in Los Angeles, CA, in November, 1982.

**For homework, each student is to pose an ethical problem and submit it before class to one of four classmates who have been identified as facilitators.**

the student into the practical application of the principles. Since our provincial licensing agency requires that young professionals pass a written examination in ethics, we use the Ontario Code. The codes are compared by Unger [6]. Fortunately, Larry Sentance of APEO headquarters helped me by providing worked examples of ethical situations and elaborations as to which sections of the code are pertinent [5]. Other sources of examples and interpretation are given by Alger et al [7]. My favorite examples are the Garrison Wyoming Rocky Mountain Fertilizer case [8] and Geza Kardo's case study of the Heron Road Bridge [9].

### IN-CLASS USE

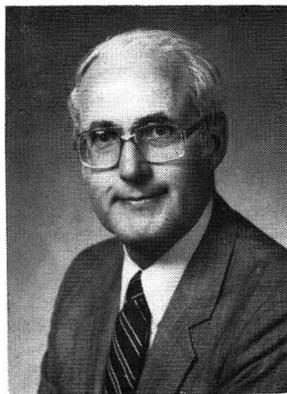
Our in-class exploration of ethics is a two-hour experience within a four-credit, 26-week long course on process analysis, professionalism, cost estimation, and process synthesis. Components of this course have been described elsewhere [10, 11, 12]. One of the required texts contains a nine-page description of micro- and macroethics, the code of ethics, and examples of interpretation [5].

For the ethics portion of the course, the code of ethics is described, and the meaning is illustrated by selected examples which are presented by the instructor. For homework, each student is to pose an ethical problem and submit it before class to one of four classmates who have been identified as facilitators. In the next class, each facilitator in turn presents to the class his/her choice of a challenging case situation. Examples are given in the Appendix to this paper. Each case is discussed in small groups of about five students, and then each group verbally reports

- What sections of the code apply
- What the code says
- What the group considered to be alternative actions
- What actions they would take

Thus, each group discussed four cases. As instructor, I have merely played the role of facilitator. If asked to judge the responses however, I would share my own views.

Often, problems on the final exam relate to



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ethics. A typical exam problem is

You are a professional engineer working for Company A. You submit a design for a new process. The plant manager, also an engineer, is quite old and has been in a management position for the last thirty-five years. Many of your colleagues feel his technical ability has virtually disappeared. The plant manager receives your proposal, but before implementing it he decides to make some small changes to increase its profitability. You realize that these changes, although profitable, could introduce a safety problem. But because of the nature of the case, you decide to keep quiet. Later, some of this process equipment blows up and a couple of workers are severely injured. Did you act unethically in this case? Discuss the case fully and make recommendations if possible.

#### STUDENT RESPONSE

Student response has been overwhelmingly favorable. They suggest that they learned a lot and enjoyed the approach taken. They do not, however, recommend that more time be spent on it.

#### OTHER IDEAS AND DISCUSSIONS

Many examples have been presented about responses to ethical situations. See, for example, the interesting series in *Chemical Engineering* [13, 14]. These have tended to report consensus viewpoints. What I enjoy about our approach has been the specific link between an established code of ethics and the situation. That is, the requirement to interpret one's actions in the context of the code.

Whistleblowing is a fascinating topic but one that should not be discussed idealistically out of context of the real possibility of being fined or blacklisted. Steps are being taken within various engineering professions [15] to help identify workable, whistleblowing procedures. Once these are in place, I can see the importance of professional

engineers from the Practice and Ethics Committee describing cases of action taken in order to illustrate how best to proceed.

#### SUMMARY

A two-hour experience on professional ethics is part of a senior level course on process analysis and professional practice. The provincial code of ethics is explained by using examples. The students then pose ethical problems and discuss/report their solution to those problems in the context of the code.

#### ACKNOWLEDGEMENT

I am pleased to acknowledge the assistance of L. C. Sentance of the Association of Professional Engineers of Ontario for his generous help in the initial presentation of this programme and to Dr. J. W. Hodgins, whose insight helped me to develop the program. The pleasure comes from the students, and I am pleased to acknowledge their contributions, through examples and discussion, to this program. □

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## APPENDIX: EXAMPLE PROBLEMS

### Case 1

There is a major energy crisis in the country. All of the company's efforts are directed toward the design and development of new energy sources for such things as a steam generation plant.

Out of the old files, you dig up what is believed to be a brilliant design of a solar heater for the steam generation plant. The idea was proposed over fifty years ago and since, at that time, there was no energy crisis and fossil fuels were cheap, the design was economically unfeasible and therefore canned. However, in the light of the present situation it would be most economical and would save the company a lot of money, as well as conserving other depleted energy resources.

Only a handful of engineers had seen the original plan and in the ensuing fifty years they had all passed away. Nobody in the company today has ever seen the design.

Because of poor economic conditions, you have recently taken a cut in salary. You see yourself as a very hard worker and have contributed much to the company in the way of process optimization, but you have received very little credit or recognition for all your work. This design would give you that recognition along with a generous suggestion bonus. The savings to the company would far exceed what you would get as a bonus. So you

make some minor adjustments to the design and submit it as an original idea. The bonus would have to be forfeited if it were known that the design was created over fifty years ago. This way, both the company and you come out ahead and no one is the loser. After all, you did the research, found the old plans, and modified them for present use. It would be unfair if you got nothing for your efforts.

Would this be ethical? (E. R.)

### Case 2

In a waste treatment process, some of the activated sludge must be removed in order to keep the recycled sludge at a specified concentration. This spent sludge is used as landfill. Recently, you have found that this sludge has been concentrating a chemical which is known to be cancer producing. By allowing this sludge to be used as landfill, this chemical is returned to the watershed through leaching. You have notified the company of the problem, but they refuse to do anything about it.

Is this ethical? (R. A. B.)

### Case 3

Within the last year, the parasite spruce budworm has infected approximately 25% of the forests in Nova Scotia. Most of the infestation is confined to northeastern Nova Scotia and Cape Breton Island, where the economy is heavily dependent on forest products. Failure to control the pest could result in the loss of this industry.

When the infestation first became apparent, the Nova Scotian government decided against spraying because the emulsifier in the spray was linked to an outbreak of a rare children's disease in New Brunswick, where spraying is carried out every summer. As an engineer with the ministry responsible for the environment, you estimate that about half the people in the province live in rural areas and that they obtain their water supplies from small, inland lakes and private wells. It is likely that the emulsifier will make its way into drinking water if spraying is carried out. Should you go along with the considerable pressure placed on you and the government by the forestry industry in the hope of saving the industry and the thousands of jobs involved? (V.)

### Case 4

You are an engineer working at a steel mill. You come in on a night shift and discover that the smelter gas from the smelter is being shunted past the electrostatic precipitators in order to make the

tonnage of steel that is required on the shift. There is a butterfly valve that can be turned so that all of the dirty gas just goes right out of the stack. Since it is at night, there are no complaints from people in the surrounding area or from the environment board. You are the engineer working on the control of the precipitators, not in the production department.

What should you do? (K. H.)

#### Case 5

I am a fourth year engineer seeking employment. In January, I am offered a job by company X and am given ten days to accept their offer. I accept their offer.

Two weeks later I receive a better offer, in pay and position. I take the second offer and tell the first company that I am unable to work for them.

1. Is this ethical?
2. Would the situation change if I was offered another job in May just before I was to report for company X?
3. Does a company expect this to happen?

## ChE letters

### SAFETY PROBLEM CHALLENGED

Dear Sir:

I read with interest Professor Jan Mewis' article, "How Much Safety Do We Need in ChE Education."

Unfortunately, the equation used by Professor Mewis to solve the tank overflow problem is not rigorous, and can give outrageously bad results. A rigorous derivation and the correct solution to the protective system problem can be found on p. 459 of *Reliability Engineering and Risk Assessment*, by E. J. Henley and H. Kumamoto, Prentice-Hall Inc., Englewood Cliffs, NJ, 1981.

I agree with Professor Mewis that all engineers should receive some training in reliability and safety analysis. Short courses, such as given by the AIChE are, in my opinion, adequate. In many European countries risk studies such as those mandated in the nuclear industry are required of all industry. I think this is very unfortunate. You really can't legislate safety; it is an individual and corporate responsibility.

**Ernest J. Henley**  
University of Houston

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## ChE book reviews

### FUNDAMENTALS OF FLUIDIZED-BED CHEMICAL PROCESSES

by J. G. Yates

Butterworth Publishers, 10 Tower Office Park, Woburn, MA 01801, 1983; \$49.95

Reviewed by L. T. Fan  
Kansas State University

This lucidly written book contains five chapters. The first, which is the longest, deals with some fundamental aspects of fluidization. The modeling of fluidized-bed reactors is discussed in the second chapter; the majority of available models are compiled. The last three chapters cover the application of fluidization technology. More specifically, chapter three focuses on the well-known Fluidized Catalytic Cracking Process and chapter four on the combustion and gasification of coal. The last chapter outlines a number of miscellaneous processes, including production of several chemicals, sulphide ore roasting, and reduction of iron ores.

Continued on page 144.

## THERMAL CONDUCTIVITY OF A HOTDOG

MICHAEL J. MATTESON AND  
JUDE T. SOMMERFELD  
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### PROBLEM STATEMENT

In a proposed new chemical engineering laboratory experiment, students are to determine the thermal conductivity of a hotdog. The procedure consists of inserting a thermistor into the center axis of the hotdog, about midway between its ends, and then totally immersing the hotdog in an agitated tub of boiling water. The thermistor is then used to measure the temperature increase of the hotdog with time. A sketch of this experiment is shown in Fig. 1.

The results of one such experiment are shown in Fig. 2. In this experiment the initial hotdog temperature was 70°F, and the boiling water temperature was 212°F. The density of the hotdog (diameter = 1 inch) may be taken as 50 lbs/ft<sup>3</sup>, and its heat capacity as 1.0 BTU/lb·°F. From these data and those of Fig. 2, determine the thermal conductivity of this hotdog. It may be assumed that the surface temperature of the hotdog is the same as the boiling water temperature (that is, the convective heat transfer coefficient at this surface is very large).

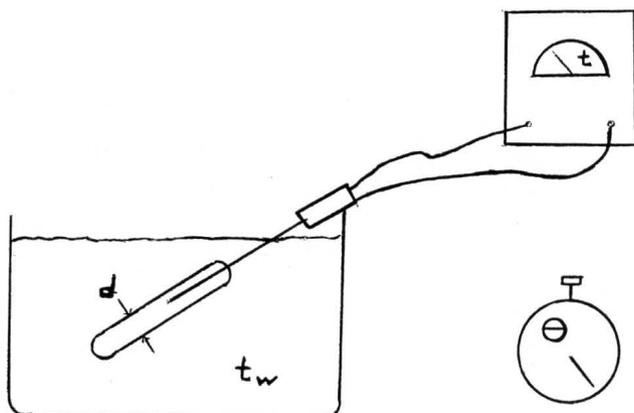


FIGURE 1. Sketch of experimental apparatus.

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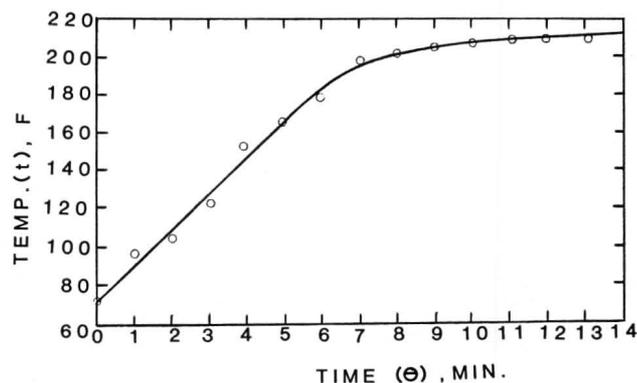


FIGURE 2. Center-line temperature (t) as a function of time (θ).

### SOLUTION

The partial differential equation for unsteady-state heating (or cooling) by conduction in one direction (radial) with cylindrical geometry is well known [1]

$$\frac{k}{\rho c_p} \left[ \left( \frac{\partial^2 t}{\partial r^2} \right) + \frac{1}{r} \left( \frac{\partial t}{\partial r} \right) \right] = \frac{\partial t}{\partial \theta} \quad (1)$$

If one makes the following conventional definitions

$$T = \frac{t_w - t}{t_w - t_o} \quad (2)$$

$$x = \frac{r}{r_o} \quad (3)$$

$$\alpha = \frac{k}{\rho c_p} \quad (4)$$

$$z = \frac{\alpha \theta}{r_o^2} \quad (5)$$

Eq. (1) becomes

$$\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial x^2} + \frac{1}{x} \cdot \frac{\partial T}{\partial x} \quad (6)$$

The boundary conditions for this problem, in terms of the new variables, are

$$(i) \quad T(1, z) = 0 \text{ for } z > 0 \quad (7)$$

$$(ii) \quad \frac{\partial T}{\partial x}(0, z) = 0 \text{ for } z > 0 \quad (8)$$

$$(iii) \quad T(x, 0) = 1 \text{ for } 0 \leq x < 1 \quad (9)$$



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**Jude T. Sommerfeld** has been a professor of ChE at Georgia Tech since 1970. He teaches courses on process control, distillation, reactor design and process design, and his research interests include energy conservation. He has also served as a consultant to numerous industrial organizations. Dr. Sommerfeld received his B.ChE degree from the University of Detroit, and his MSE and PhD degrees in chemical engineering from the University of Michigan. (R)

Note that end effects were neglected in the derivation of Eq. (1).

Eq. (6) with its associated boundary conditions is a standard Sturm-Liouville system [2] and its solution is given by

$$T(x,z) = \sum_{n=1}^{\infty} \frac{2 \exp(-\lambda_n^2 z)}{\lambda_n J_1(\lambda_n)} J_0(\lambda_n x) \quad (10)$$

where  $\lambda_n$  is the  $n^{\text{th}}$  root resulting from solution of the following equation

$$J_0(\lambda) = 0 \quad (11)$$

From Eq. (10), the expression for the center-line temperature (at  $x = 0$ ) is

$$T(0,z) = \sum_{n=1}^{\infty} \frac{2 \exp(-\lambda_n^2 z)}{\lambda_n J_1(\lambda_n)} \quad (12)$$

In many practical calculations, it is necessary to consider only the first term in the infinite series summation of Eq. (12).

Choosing a value of  $\theta = 5$  min ( $= 1/12$  hr), we read from Fig. 2 a value for the center-line temperature of  $166^\circ\text{F}$ . Hence

$$T(0,z) = \frac{212 - 166}{212 - 70} = 0.324$$

As a first approximation, we consider only the first term on the right-hand side of Eq. (12). The

first root of Eq. (11) is  $\lambda_1 = 2.405$  and  $J_1(\lambda_1) = 0.5191$  [3]. Equating this first term to  $T(0,z)$  and solving for  $z$ , we find that  $z = 0.276$ . Hence

$$\alpha = \frac{r_0^2 z}{\theta} = \frac{(1/24)^2 (0.276)}{(1/12)} = 0.00576 \text{ ft}^2/\text{hr}$$

$$\text{and } k = \alpha \rho c_p = (0.00576) (50) (1.0) = 0.288 \text{ BTU/hr}\cdot\text{ft}\cdot^\circ\text{F}$$

Let us evaluate the second term in the summation of Eq. (12) to determine its significance. Here,  $\lambda_2 = 5.520$  and  $J_1(\lambda_2) = -0.3403$  [3]. Using the value of  $z$  determined above, we find the value of this second term to be equal to  $-0.000234$ , which is less than  $0.1\%$  of the first term.

Graphical solutions to Eq. (10) or (12) also exist in the form of the Gurney-Lurie charts. Here,  $m = k/r_0 h = 0$  because  $h$  is infinite, in accordance with the earlier assumption regarding the surface temperature. Again using the same center-line data point at  $\theta = 5$  min, we find from the Gurney-Lurie chart for long cylinders [4] that  $z = 0.28$ . Hence,  $\alpha = 0.058 \text{ ft}^2/\text{hr}$  and  $k = 0.29 \text{ BTU/hr}\cdot\text{ft}\cdot^\circ\text{F}$ . □

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## NOMENCLATURE

$c_p$	heat capacity of cylinder, BTU/lb $\cdot^\circ\text{F}$
$h$	surface heat transfer coefficient, BTU/hr $\cdot\text{ft}^2\cdot^\circ\text{F}$
$J_0$	Bessel function of the first kind and of order zero
$J_1$	Bessel function of the first kind and of order one
$k$	thermal conductivity of cylinder, BTU/hr $\cdot\text{ft}\cdot^\circ\text{F}$
$m$	$k/r_0 h$
$r$	variable radius, ft
$r_0$	radius of cylinder, ft
$T$	dimensionless temperature = $(t_w - t) / (t_w - t_0)$
$t$	variable temperature of cylinder, $^\circ\text{F}$
$t_0$	initial temperature of cylinder, $^\circ\text{F}$
$t_w$	water temperature, $^\circ\text{F}$
$x$	dimensionless radius = $r/r_0$
$z$	dimensionless time = $\alpha\theta/r_0^2$
$\alpha$	thermal diffusivity of cylinder, $\text{ft}^2/\text{hr}$ $= k/\rho c_p$
$\lambda_n$	$n$ -th root of the equation $J_0(\lambda) = 0$
$\rho$	density of cylinder, lbs/ft $^3$
$\theta$	time, hrs

## DIMENSIONLESS EDUCATION

GRAHAM F. ANDREWS  
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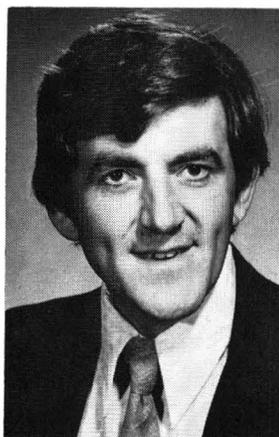
CONSIDER FOR A MOMENT the confusion imposed on engineering undergraduates. At some point in a junior-level fluid mechanics class the subject is dropped for a class or two while the students are presented with a series of strange propositions.

(a) Mass, length, and time are "fundamental dimensions." Although this probably seemed self-evident to Osborne Reynolds, it sounds very strange to the post-Einstein generation. Mass, length, and time, far from being "fundamental", all depend on how fast you are going. If pressed, the professor may point out that, in fact, any set of three dimensions (velocity, energy, and area, for instance) could serve as the basis on which the others could be defined. Mankind has simply chosen mass, length, and time as a convenient group and set up standards for them at various places around the world. Even this explanation leaves some students uneasy; if mankind selected these three dimensions at random and then labelled them fundamental, it is surely guilty of, at best, abuse of the English language.

(b) Buckingham's  $\pi$  Theorem. This is the centerpiece of the subject, and it is totally unlike any theorem the student has ever seen before or (with the possible exception of the Phase Rule) will ever see again. No proof is offered. In fact, a survey of the standard works (Becker [1] gives a comprehensive list) leaves doubt about what would constitute an adequate proof.

(c) Dimensionless groups. The student has invested considerable effort in grasping concepts like pressure and viscosity, but suddenly these hard-won ideas disappear, subsumed into groups named after dead foreigners he has never heard of. This is not reassuring.

(d) The purpose of dimensional analysis is, in effect, to reduce the number of variables in a problem. This idea may be introduced in the context of fluid flow in smooth pipes where five vari-



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ables (pressure gradient, pipe diameter, fluid velocity, viscosity, and density) are reduced to two (the Reynolds number and friction factor). This is obviously extremely useful. It allows us to draw one graph good for all fluids in all smooth pipes, and vastly reduces the number of experiments we must do to develop the form of the general pressure drop-flow rate relation. But, explained in this fashion, this ability to "reduce the number of variables" is disconcerting to the student.

Consider, for example, the pendulum problem. There will be general agreement in a class that the period,  $t$ , of a simple pendulum will depend on its mass  $m$ , its length  $l$ , and its gravitational acceleration  $g$ . Applying dimensional analysis to these quantities gives the solution

$$t \sqrt{g/l} = \text{constant} \quad (1)$$

The mass cannot appear in the solution because no other quantity involved contains the mass dimension, so we cannot create a dimensionless group involving  $m$ . So, having said very little about pendulums and absolutely nothing about the laws of dynamics, we have proven that the period is independent of the pendulum mass and proportion-

al to the square root of its length. At first glance this appears close to witchcraft.

In summary, the traditional approach to teaching dimensional analysis is confusing. The purely formal procedures for deriving the form of dimensionless groups are often stressed while basic questions go unanswered. These include "Why does it work?" and "If equations written as dimensionless groups are so simple and descriptive, why aren't all equations written this way?" (Bernoulli's equation is a case in point.) Furthermore, it leaves the unfortunate impression that dimensional analysis is a branch of transport phenomena, an impression that is reinforced when the dimensionless numbers that arise in other subjects are not identified as such, being named not after dead foreigners but after living Americans (Thiele modulus) or even no one at all (compressibility, etc.). Consequently, students may not add dimensional analysis to their armory of techniques for confronting new problems. As an example, try the following problem on a senior or graduate class: "A zero-order reaction occurs at rate  $r$  gm/cm<sup>3</sup> s in an isothermal, semi-infinite slab of porous catalyst in which the reactant diffusivity is  $D$  cm<sup>2</sup>/s. What happens to the reactant uptake rate per unit area of the slab when its concentration at the slab surface is doubled?" This problem, and others like it, can be solved by a simple application of Buckingham's theorem, but few will attempt it simply because they do not associate this theorem with kinetics.

### A BETTER APPROACH

To determine how dimensional analysis should be taught, we start from its role in engineering. Engineers are often asked to solve real-world problems where no exact mathematical solution is possible. It is here that dimensional analysis is a powerful tool, combined with either physical models (a procedure known variously as the empirical approach, similarity solutions, or the scale-up method) or with the unsolvable differential equations describing the problem (see for example Bird, Stewart and Lightfoot's [2] treatment of free convection on a vertical wall). It is valid and useful in all engineering disciplines and in all branches of chemical engineering, appearing most often in transport phenomena only because turbulence is our most intransigent real-world phenomenon.

It follows that the topic should be included in the "introduction to engineering" course that freshmen are usually required to take. The author

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**Engineers are often asked to solve real-world problems where no exact mathematical solution is possible. It is here that dimensional analysis is a powerful tool . . .**

---

has been doing this successfully for a number of years at SUNY at Buffalo using the method described below.

The main difficulty is textbooks. Although dimensional analysis is well covered in the standard transport texts (notably Bennett and Myers [3]), they are of little help in freshman courses where the examples must be kept simple and the context general. Of the many texts available for "introduction to engineering" courses, only one [4] known to the author includes the subject. However, they all introduce the idea of fundamental and derived dimensions as the basis of unit systems, and many introduce the idea that all terms in an equation must be dimensionally homogeneous. This is taken as the starting point for giving some insight into what dimensional analysis is, and why it works.

### Principle

You can't add  $x$  oranges to  $y$  apples and get  $z$  bananas.

### Or

All terms to be added, subtracted or equated in an equation must have the same dimensions.

This intuitively obvious principle can be demonstrated with known equations such as Einstein's  $E = mc^2$ , Bernoulli's equation, and the equation for sonic velocity in a gas. It is important to point out at this stage that dimensional consistency is a condition for the existence of an equation. Consistency of the units is an additional requirement if the equation is to give the right answer.

### Corollary

Any relation between physical quantities can be written as a relation between dimensionless groups.

Again, this is easy to demonstrate using the equations introduced above.

### Observation

There are fewer dimensionless groups than dimensional variables. This is immediately ap-

parent from the previous exercise. Einstein's equation goes from three variables ( $E$ ,  $m$ ,  $c$ ) to one group ( $E/mc^2$ ), Bernoulli's equation from five variables to two groups (an Euler number and a Froude number), and the equation for hoop stresses in a thin-walled pressure vessel goes from four variables to two groups. Buckingham's theorem is now introduced as the answer to the natural question of how many groups there will be in a given situation.

With this background, exercises like the pendulum problem seem far less like witchcraft. We hypothesize a relationship between the quantities,  $m$ ,  $l$ ,  $g$ ,  $t$ , but we are not free to arrange these variables in any fashion we choose. Their possible arrangements are constrained by the requirement that they be dimensionally consistent. One way to ensure this consistency is to arrange the variables in dimensionless groups. Buckingham's theorem tells us how many groups are required. No combination of the variables which includes  $m$  can be dimensionless, so  $m$  must not be relevant to the problem.

Given this introduction, the students can accept the work of counting the independent fundamental dimensions and determining the form of the dimensionless groups. These are now seen for what they are—merely useful, formal techniques for deriving logical results. Several excellent problems involving just one group are available for practice. They include the frequency produced by a guitar string, the drag force on an automobile, the height of the bow wave on a ship, the power required to stir a liquid, the pressure generated by a pitot tube, the speed of descent of a parachute, and centrifugal force.

### REYNOLDS' SIMILARITY PRINCIPLE

If a physical situation can be completely defined by  $n$  variables, or  $(n-m)$  dimensionless groups, it follows logically that in order for two situations to be identical, the simplest condition we need invoke is that the dimensionless groups must have the same values in the two situations. This important principle is the basis of both physical modelling and its inverse process, scale-up. While it is easy to state, it is difficult for students to grasp. The idea that, for example, lead shot falling through water is somehow "identical" to a tennis ball falling through air is very strange at first; the size, velocity and fluid properties are, after all, different in the two cases.

This is a situation where "one in the eye is

worth three in the ear." Films showing model parachutes opening underwater, or Reynolds experiment done with various fluids and pipe diameters, are more convincing than hours of explanation. Old war movies are also good teaching aids. The physical situation (the bow wave, wave-induced oscillations, etc.) of the model ships that are "torpedoed" in these movies is always observably different from that of a real ship, in spite of the best efforts of the special effects men of that era. (In fact, given the number of variables, it is impossible to make all the relevant dimensionless groups the same on the two scales.) In *The Dam Busters*, the story of the destruction of the Ruhr dams by bombs that bounced along the surface of the impounded lakes, Barnes-Wallace, the engineer-hero (a fine role model for any engineering student), is seen testing his ideas by bouncing ping-pong balls across a swimming pool.

### WHY DOES IT WORK?

Experience shows that, even with the best teaching techniques, dimensional analysis makes students uneasy. The difficult question inevitably arises: "How can we learn so much about pendulums while saying so little about the laws of dynamics?" The answer is outside engineering in metaphysics. Dimensions are human inventions that we impose on nature in order to understand it scientifically. Einstein's description of scientific theories as "free creations of the human mind" applies equally well to the dimensions that underlie the theories. Mass, length, and time are fundamental only in the sense that they were defined very early in human history in response to very fundamental questions: "How much grain should I store for the winter?" "How far from my house does my neighbor's land start?" "How long will it take to reach the next waterhole?"

To those who doubt this view, it can be pointed out that other beings (with other senses, on other planets) may have invented a completely different set of dimensions. A race of scientific dogs, for example, may well believe "smell intensity" to be extremely fundamental. Intelligent deep sea fish, in their naturally-buoyant, constant-temperature environment, would never have defined the concepts of weight and temperature in the same way that early man did. Or consider a planet with no moon and no tilt to its axis, that revolved on its axis once for every rotation of the planet around its star. The inhabitants would still grow old and die, but their lifetimes could not be divided into days, months and years because these units, which

imposed the concept of time on our ancestors, would not exist. Time may well appear to them not as a fundamental dimension, but as a esoteric consequence of the second law of thermodynamics.

Uneasiness about dimensional analysis arises because subconsciously we hold a different view of dimensions. Mass, length, and time were defined so long ago and appear so early in our education that we think of them as self-evident "things" and not as human inventions. Deep down we cling to Newton's view of "absolute space" and "absolute, true mathematical time of itself and by its own nature flowing uniformly without regard to anything external." We forget that Newton's basis for these views was not scientific but theological. To him they were perfect ideas in the mind of God. Even the theory of relativity, which destroyed the idea of mass, length, and time as "absolute," could not change their status as "fundamental."

Dimensional analysis is nature's way of reminding us that it is universal and can hardly be affected by the particular set of dimensions our species happens to choose and label "fundamental." It follows that if we wish to describe nature we must use variables from which all our concepts have been cancelled, i.e. dimensionless groups. If the dimensionless groups describing two physical situations are the same, then the "nature" of the situations must be identical, irrespective of whether we are dealing with lead shot or tennis balls. Imposing our own concepts onto our descriptions of nature only increases their complexity (by increasing the number of variables) and reduces their universality. If we wished to communicate our knowledge of fluid mechanics to engineers on the timeless planet mentioned above, we could send diagrams of Reynolds' experiment with the laminar/turbulent transition marked with the binary equivalent of 2300. This would be understood. The markings  $\nu = 1$  cS,  $d = 1$  cm,  $V = 2.3$  cm/s would be incomprehensible, even in binary.

Is it worthwhile trying to explain this to a group of freshmen? Perhaps it is. Mankind's search for wisdom has always been slowed by our arrogance, our illusion that we occupy a uniquely privileged position in the universe. Assigning a special position to our planet hindered acceptance of Copernican astronomy. Assigning a special position to our species hindered acceptance of the theory of evolution. Similarly, assigning a special position to our concepts of mass, length, time, etc. hinders acceptance of the similarity principle (and, incidentally, relativity). If the next genera-

tion of engineers understands this, they will be a little wiser for it.

## CONCLUSIONS

Dimensional considerations are central to chemical engineering. They are the basis of scale-up, they allow us to use just one chart for j-factors etc. for all fluids and scales of operation, and sometimes they enable us to derive quite detailed results just from the form of differential equations. Given this importance, the conventional way of teaching dimensional analysis is unsatisfactory. Routine procedures for deriving dimensionless groups are often stressed over questions of why and how it works, and the student gets the distinct impression that the entire subject is a branch of transport phenomena.

Since dimensional analysis is applicable to all branches of engineering, it should be introduced in freshman or sophomore general engineering courses. Junior transport phenomena students can then appreciate that they are seeing a particular example of a general truth. The subject is best taught by writing known equations as relations between dimensionless groups. A comparison of the dimensional and dimensionless forms then shows Buckingham's theorem as a direct consequence of the dimensional homogeneity of equations.

Mankind invented mass, length, time, etc., and then recombined them into more complex concepts (velocity, energy, etc.). Science got underway by describing nature as the relationship between those concepts. But since nature cannot be bound by human inventions, all these relationships (even the most profound) are necessarily of such a form that our concepts, the dimensions, cancel out. They are most simply written as relations between dimensionless groups, and it is only in this form that we could communicate our knowledge to other species whose science may have developed from a completely different set of dimensions. Nature itself is dimensionless. □

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# THE THERMODYNAMIC FUNDAMENTALS OF EXERGY

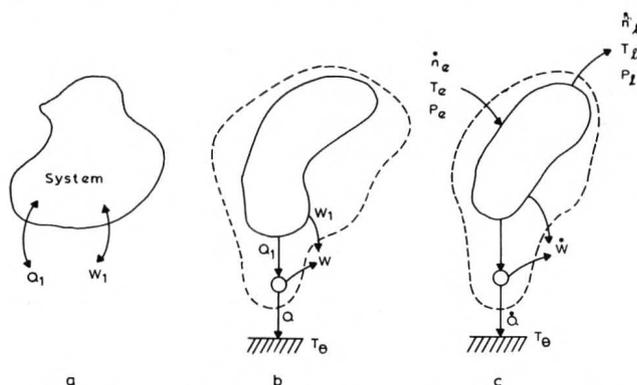
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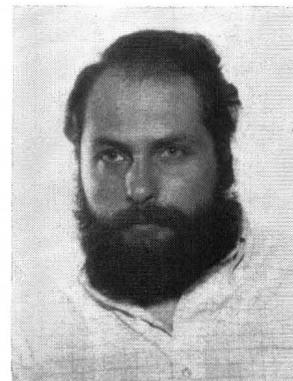
**A**VAILABILITY IS A thermodynamic function whose difference between any two states of a system gives the limiting (reversible) value of work associated with a given change and environment conditions. Changes in availability, therefore, can be used to evaluate the thermodynamic performance of a process.

Exergy is shown to be an extension of the concept of availability when it becomes necessary to quantify a flowing stream's capacity to produce useful work, given stream and environment conditions. Exergy can therefore be thought of as a property of the stream (for a given environment), and can be used as a basis for assigning an economic value to it, based on its work producing capacity.

A stream's exergy is a function of the reference environment. Since this choice is completely arbitrary, except for the requirement that the environment be in equilibrium, computed values of exergy and exergetic efficiency can only be used for comparison (for a given reference state), not in an absolute sense. The equilibrium constraint, on the other hand, eliminates from consideration many realistic, non-equilibrium environments.



**FIGURE 1.** a) Closed system. b) Closed system showing boundaries needed for availability analysis. c) Open system showing boundaries needed for availability analysis.



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Once these limitations are understood, however, exergy can be fruitfully used in process analysis and design, in cases where it is necessary to quantify the efficiency with which useful work is obtained from the process streams [1-9]. The thermodynamic fundamentals of exergy are developed below, emphasizing similarities and differences between exergy and availability.

## AVAILABILITY

Availability is a thermodynamic function whose difference between any two given equilibrium states of a system is a measure of the maximum work obtainable from (or the minimum work required to effect) the given change. Since, as will be shown below, the concept of exergy follows quite naturally from the closely related thermodynamic function known as availability, the latter will be considered first.

Consider (Fig. 1.a) a closed, simple system i.e., a system whose boundaries are impermeable to mass flow, contains no internal adiabatic, impermeable, or rigid boundaries, and is not acted upon by force fields or inertial forces [10]. For the present analysis, the environment with which the system interacts can be imagined as consisting

of a heat reservoir [11] at a temperature  $T_0$ , and an isobaric work reservoir at a pressure  $P_0$ . For any differential process, we can write (Fig. 1.a)

$$d\bar{U} = \delta Q_1 - \delta W_1 \quad (1)$$

where  $\delta Q_1$  and  $\delta W_1$  represent inexact differentials. Now consider Fig. 1.b, where any Carnot engine needed to transfer heat reversibly between the system and the environment has been added. The following relations apply

$$d\bar{S}_r = -\frac{\delta Q}{T_0} \quad (2)$$

$$d\bar{S}_s = \frac{\delta Q}{T_0} + \delta \bar{S}^* \quad (3)$$

$$d\bar{U} = \delta Q - \delta W \quad (4)$$

$$\delta \bar{S}^* \geq 0 \quad (5)$$

where  $\delta \bar{S}^*$  is the entropy created as a result of the (irreversible) processes occurring within the boundaries shown in Fig. 1.a. Therefore

$$\delta W + T_0 \delta \bar{S}^* = T_0 d\bar{S} - d\bar{U} \quad (6)$$

For finite changes

$$W + T_0 \bar{S}^* = T_0 \Delta \bar{S} - \Delta \bar{U} \quad (7)$$

Since we are interested in useful work, we must subtract from  $W$  the portion that constitutes expansion work against the surrounding pressure. For reversible operation, therefore, the maximum useful work that can be obtained from a closed system in going from a specified initial to a specified final state, while interacting with surroundings at  $P_0$  and  $T_0$ , is

$$W_{\max, \text{net}} = T_0(\bar{S}_f - \bar{S}_i) - (\bar{U}_f - \bar{U}_i) - P_0(\bar{V}_f - \bar{V}_i) \quad (8)$$

Eq. (8), as written, is not restricted to cases where  $\bar{V}_f > \bar{V}_i$ . If a partially evacuated container fitted with a frictionless piston and filled with an ideal gas is compressed reversibly and isothermally by the surroundings up to  $P_0$ , the work obtained is now  $P_0(\bar{V}_i - \bar{V}_f)$  minus the compression work done by the environment on the container,  $T_0(\bar{S}_i - \bar{S}_f)$ .

The right hand side of Eq. (8) is only a function of the end states,  $T_0$  and  $P_0$ ; the following state function is normally called availability

$$-\bar{B} = T_0 \bar{S} - \bar{U} - P_0 \bar{V} \quad (9)$$

so that finally

$$W_{\max, \text{net}} = -\Delta \bar{B} \quad (10)$$

If we now consider an open system, under steady

**Exergy is shown to be an extension of the concept of availability when it becomes necessary to quantify a flowing stream's capacity to produce useful work, given stream and environment conditions.**

state conditions, the First Law now yields, (Fig. 1.c)

$$0 = \dot{Q} - \dot{W} + \sum_e H_e \dot{n}_e - \sum_l H_l \dot{n}_l \quad (11)$$

where summations are over all entering and leaving streams, respectively, and  $\dot{n}_e$  may differ from  $\dot{n}_l$  if chemical reactions occur. The corresponding entropy balance, with  $T_0$  denoting the heat reservoir's temperature, reads

$$0 = \frac{\dot{Q}}{T_0} + \dot{\bar{S}}^* + \sum_e S_e \dot{n}_e - \sum_l S_l \dot{n}_l \quad (12)$$

substituting for  $\dot{Q}$

$$\dot{W} = \sum_e (H_e - T_0 S_e) \dot{n}_e - \sum_l (H_l - T_0 S_l) \dot{n}_l - T_0 \dot{\bar{S}}^* \quad (13)$$

For reversible operation

$$\dot{W}_{\max} = \sum_e (H_e - T_0 S_e) \dot{n}_e - \sum_l (H_l - T_0 S_l) \dot{n}_l \quad (14)$$

As before (see Eq. 8), the maximum (reversible) work obtainable is a function only of the end states and the environment's conditions. Accordingly, we can define an availability for flow systems [3]

$$B' = H - T_0 S \quad (15)$$

$$W_{\max} = \sum_e B'_e \dot{n}_e - \sum_l B'_l \dot{n}_l \quad (16)$$

Given an environment which is the sole net heat source (or sink) with which the system under consideration interacts, and which is characterized by  $T_0$  and  $P_0$  (closed systems) or  $T_0$  (open systems), differences in availability, therefore, represent limiting values for the maximum (minimum) work that can be obtained from (that is required to achieve) any given change.

## EXERGY

If we define efficiency as  $\dot{W}/\dot{W}_{\max}$ , it follows from the preceding discussion that, for open systems under steady state conditions and with given end states, the thermodynamic performance (efficiency) of a process can be analyzed by means of the function known as availability.

Even though availability is a property of the

stream (given  $T_0$ ), only changes in availability are of interest, since  $B'$  is only defined up to an arbitrary constant. Exergy is a function introduced to overcome this limitation; this is done by selecting an equilibrium environment as the reference state. Then, the availability change arising from the complete equilibration of any given stream with the environment is defined as the stream's exergy.

Specifically, for a flowing process stream of components  $1, \dots, j, \dots, n$  at arbitrary conditions  $T, P, y_j$ , exergy is defined as the maximum work (per mole of stream) that can be obtained upon its equilibration with the environment, the latter being characterized by  $T_0, P_0$  and  $\hat{\mu}_{j0}$ , when heat interactions take place with a single source-sink at  $T_0$ . Here,  $\hat{\mu}_{j0}$  denotes the chemical potential of component  $j$  in the environment.

$$\begin{aligned} \text{Exergy} = \psi = & H_e(T_e, P_e, y_{je}) - T_0 S_e(T_e, P_e, y_{je}) \\ & - \sum_{j=1}^n y_{je} \hat{\mu}_{j0}(T_0, P_0, y_{j0}) \end{aligned} \quad (17)$$

$$\dot{W}_{\max} = \left( \sum_{j=1}^n \dot{n}_j \right) \left( H_e - T_0 S_e - \sum_{j=1}^n y_{je} \hat{\mu}_{j0} \right) \quad (18)$$

Eq. (18) can be obtained either by direct calculation of the various heat and work interactions resulting from the reversible equilibration process, or by setting outlet conditions equal to environment conditions in Eq. (16).

In analyzing any particular process, therefore, availability balances can be made around the various process blocks (unit operations) to determine thermodynamic efficiencies. Exergy, on the other hand, is useful if, in addition to the thermodynamic efficiency of a given unit operation, we are interested in analyzing how the overall process utilizes the capacity to produce useful work of all its streams.

An availability balance around a turbine, for example, will yield a value for its isentropic efficiency. The exhaust stream exergy, however, is not taken into account in such an analysis. If the exhaust stream is neither recycled nor used downstream, for example, it should have as low an exergy as possible. For energy recovery schemes, on the other hand, a compromise must be reached between exhaust exergy and power output.

It should be emphasized, however, that since the choice of the reference environment is arbitrary, except for the requirement that it must be in chemical equilibrium, comparisons are only

meaningful for a particular ground state.

## EXERGY BALANCES

In defining exergy, the requirement that the environment be in chemical equilibrium has been introduced at the outset, since exergy has been defined as a maximum work. It should be clear that only in the limit where equilibration with the environment occurs reversibly is the resulting work maximum and path-independent. If irreversibilities are allowed in the hypothetical equilibration process, then the work becomes path-dependent and exergy loses its meaning; it is no longer meaningful to quantify a stream's capacity for producing work, since we no longer have a "measuring rod" (the maximum work). In this section, the above considerations will be translated into thermodynamic relationships and the concept of an exergy balance will be developed.

Consider (Fig. 2) a steady process. Whenever heat interactions result in a finite change in process temperature, an infinite series of differential Carnot engines, rather than a single engine, must be used. Since there may be any number of such infinite series, with  $\dot{Q}_1$  referring to the system (see Eq. (1) for sign convention)

$$\dot{W}_{\text{Carnot}} = - \sum \int \eta \delta \dot{Q}_1 \quad (19)$$

where the summation has as many terms as process temperature changes, and  $\eta$  is the Carnot efficiency,  $1 - T_0/T$ . Therefore

$$\dot{W} = \sum \dot{W}_1 - \sum \int \eta \delta \dot{Q}_1 \quad (20)$$

where the first summation contains as many terms as there are adiabatic work interactions

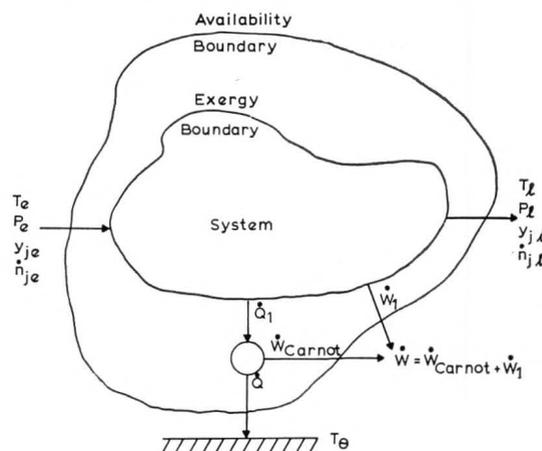


FIGURE 2. Open system. Availability and exergy boundaries are shown.

across the exergy boundary (Fig. 2).

Eq. (13) can now be rewritten in terms of heat and work interactions taking place across the exergy boundary (the actual system's boundary)

$$\sum \dot{W}_1 - \sum \int \eta \delta \dot{Q}_1 = \sum_e (H_e - T_\theta S_e) \dot{n}_e - \sum_\ell (H_\ell - T_\theta S_\ell) \dot{n}_\ell - T_\theta \dot{S}^* \quad (21)$$

To obtain an exergy balance, consider the quantity

$$\dot{X} = \sum_e \left( \sum_{j=1}^n y_{je} \hat{\mu}_{j\theta} \right) \dot{n}_e - \sum_\ell \left( \sum_{j=1}^n y_{j\ell} \hat{\mu}_{j\theta} \right) \dot{n}_\ell \quad (22)$$

Rearranging

$$\dot{X} = \sum_{j=1}^n \dot{n}_{je} \hat{\mu}_{j\theta} - \sum_{j=1}^n \dot{n}_{j\ell} \hat{\mu}_{j\theta} = \sum_{j=1}^n (\dot{n}_{je} - \dot{n}_{j\ell}) \hat{\mu}_{j\theta} \quad (23)$$

For non-reacting components,  $\dot{n}_{je} = \dot{n}_{j\ell}$ ; for reacting components, on the other hand, stoichiometric constraints apply, so that

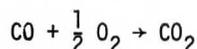
$$\sum_{j=1}^n (\dot{n}_{je} - \dot{n}_{j\ell}) \hat{\mu}_{j\theta} = (\dot{n}_{ke} - \dot{n}_{k\ell}) \sum_{j=1}^n \nu_j \hat{\mu}_{j\theta} \quad (24)$$

where  $(\dot{n}_{ke} - \dot{n}_{k\ell})$  is the reaction rate (molar basis) of any arbitrary reacting component, and  $\nu_j$  is the  $j^{\text{th}}$  component's stoichiometric coefficient.

The summation on the right hand side of Eq. (24) represents the sum of Gibbs energy changes resulting from all reactions actually taking place in the process under consideration, if they were to occur in the environment. However, as discussed above, the latter must be in equilibrium, hence these chemical potentials must necessarily satisfy

$$\sum_{j=1}^n \nu_j \hat{\mu}_{j\theta} = 0 \quad (25)$$

Eq. (25) is a direct consequence of the equilibrium constraint without which, as discussed above, exergy cannot be defined. Its significance can best be shown by means of an example: suppose we consider a process where the reaction



takes place. Then, for an environment containing specified mole fractions of  $\text{CO}_2$  and  $\text{O}_2$ , and no measurable amount of  $\text{CO}$ , the equilibrium constraint imposes a non-zero, trace mole fraction of  $\text{CO}$ . As will be shown in the next section, in calculating the exergy of a flowing stream, this quantity

is explicitly or implicitly calculated.

Because of Eq. (25), we can now rewrite Eq. (21) as an exergy balance

$$\sum \dot{W}_1 - \sum \int \eta \delta \dot{Q}_1 = \sum_e (H_e - T_\theta S_e - \sum_{j=1}^n y_{je} \hat{\mu}_{j\theta}) \dot{n}_e - \sum_\ell (H_\ell - T_\theta S_\ell - \sum_{j=1}^n y_{j\ell} \hat{\mu}_{j\theta}) \dot{n}_\ell - T_\theta \dot{S}^* \quad (26)$$

Taking into account the definition of exergy,

$$\sum \dot{W}_1 - \sum \int \eta \delta \dot{Q}_1 = \sum_e \psi_e \dot{n}_e - \sum_\ell \psi_\ell \dot{n}_\ell - T_\theta \dot{S}^* \quad (27)$$

From Eq. (20), it follows that the left hand side of Eqs. (13) and (27) are identical. Consequently, so are the respective right hand sides. Thus, from a strictly thermodynamic viewpoint, no new information has been gained from the introduction of exergy. Moreover, in deriving Eq. (27), the condition of chemical equilibrium has been imposed upon the environment.

It is the above mentioned possibility of using exergy as a basis for the quantification of the work producing capacity of a stream that justifies its use, at the expense of introducing arbitrary restrictions on the environment's characteristics. Exergetic efficiency is defined as

$$\eta_{\text{ex}} = \frac{\text{rate of generalized exergy transport from control volume}}{\text{rate of generalized exergy transport into control volume}} \quad (28)$$

In computing exergy flows,

• exergy associated with any stream is given by

$$(H - T_\theta S - \sum_{j=1}^n y_j \hat{\mu}_{j\theta})$$

• heat interactions are converted into exergy flows by introducing a Carnot efficiency (thus, for example, if the process were isothermal and  $T_e = T_l = T_\theta$ , there would be no heat flux contribution to exergy even under non-adiabatic conditions).

• all work interactions are equal to corresponding exergy fluxes. Therefore,

$$\eta_{\text{ex}} = \frac{\sum_\ell (H_\ell - T_\theta S_\ell - \sum_{j=1}^n y_{j\ell} \hat{\mu}_{j\theta}) \dot{n}_\ell + \sum \dot{W}_1 - \sum \int \eta \delta \dot{Q}_1}{\sum_e (H_e - T_\theta S_e - \sum_{j=1}^n y_{je} \hat{\mu}_{j\theta}) \dot{n}_e} = 1 - \frac{T_\theta \dot{S}^*}{\sum_e (H_e - T_\theta S_e - \sum_{j=1}^n y_{je} \hat{\mu}_{j\theta}) \dot{n}_e} \quad (29)$$

If thermodynamic efficiency is evaluated using availability rather than exergy, then, from Eq. (13) we obtain

$$\eta = \frac{\dot{W} + \sum_{\ell} (H_{\ell} - T_{\theta} S_{\ell}) \dot{n}_{\ell}}{\sum_{\ell} (H_{\ell} - T_{\theta} S_{\ell}) \dot{n}_{\ell}} = 1 - \frac{T_{\theta} \dot{S}^*}{\sum_{\ell} (H_{\ell} - T_{\theta} S_{\ell}) \dot{n}_{\ell}} \quad (30)$$

which has a different numerical value than  $\eta_{ex}$ . As stated before, availability balances provide a complete description of the efficiency of the process under study. Exergy is introduced when, in addition, streams are ranked according to their potential for work production.

In Eq. (29) it must be noted that, if some work interaction terms are negative, or any heat interaction terms are positive, they should be included in the denominator with a positive sign according to the definition in Eq. (28). Eq. (29), as written, is only valid for positive work and negative heat interactions. (See Eq. (1) for sign convention.)

#### CALCULATION OF THE EXERGY OF A FLOWING STREAM

Eq. (17) can be rewritten as follows,

$$\begin{aligned} \psi &= H(T, P, y) - T_{\theta} S(T, P, y) \\ &- H(T_{\theta}, P_{\theta}, y) + T_{\theta} S(T_{\theta}, P_{\theta}, y) \\ &+ \sum_{j=1}^n y_j \left[ \bar{H}_j(T_{\theta}, P_{\theta}, y) - T_{\theta} \bar{S}_j(T_{\theta}, P_{\theta}, y) - \hat{\mu}_{j\theta} \right] \quad (31) \end{aligned}$$

This can be expressed as

$$\begin{aligned} \psi &= \int_{T_{\theta}}^T c_p(P) \left( 1 - \frac{T_{\theta}}{T} \right) dT + \int_{P_{\theta}}^P R/P \left( \frac{\partial Z(T_{\theta})}{\partial \ln T} \right)_P dP \\ &+ T_{\theta} \int_{P_{\theta}}^P \frac{R}{P} \left( Z(T_{\theta}) + T_{\theta} \left( \frac{\partial Z(T_{\theta})}{\partial \ln T} \right)_P \right) dP \\ &+ \sum_{j=1}^n y_j \left( \hat{\mu}_j(T_{\theta}, P_{\theta}, y_j) - \hat{\mu}_{j\theta}(T_{\theta}, P_{\theta}, y_{j\theta}) \right) \quad (32) \end{aligned}$$

If we consider the case of an ideal gas stream,

$$\psi = \int_{T_{\theta}}^T c_p \left( 1 - \frac{T_{\theta}}{T} \right) dT + RT_{\theta} \ln \frac{P}{P_{\theta}} + \sum_{j=1}^n y_j (\hat{\mu}_j - \hat{\mu}_{j\theta}) \quad (33)$$

In the exergy literature, the three terms on the right hand side are called,

- "thermal availability"

**Exergy introduces no new thermodynamic information, but is useful in ranking process streams according to their potential for producing useful work . . . it is used to treat problems that require both economic and thermodynamic analysis.**

- "pressure availability"
- "chemical availability"

P-V-T data are needed in order to evaluate the pressure availability for streams which cannot be treated as ideal gases.

The last contribution to Eq. (33) is the work that can be obtained when a stream component already at  $T_{\theta}$  and  $P_{\theta}$  is reversibly equilibrated with the environment.

As an example, suppose a stream contains CO, while the reference environment contains quantities of  $O_2$  and  $CO_2$ . Then, for an equilibrium environment containing  $CO_2$  and  $O_2$

$$\hat{\mu}_{\theta CO} + \frac{1}{2} \hat{\mu}_{\theta O_2} - \hat{\mu}_{\theta CO_2} = 0 \quad (34)$$

Assuming ideal gas behavior, and for  $P_{\theta} = 1$  bar

$$\hat{\mu}_{\theta i} = \mu_i^{\circ}(T_{\theta}) + RT_{\theta} \ln y_{\theta i} \quad (35)$$

which, when substituted into Eq. (34), yields

$$RT_{\theta} \ln y_{\theta CO} = \Delta G^{\circ}(T_{\theta}) - RT_{\theta} \left[ \ln y_{\theta CO_2} - \frac{1}{2} \ln y_{\theta O_2} \right] \quad (36)$$

so that, finally,

$$\hat{\mu}_{CO}(T_{\theta}, P_{\theta}, y_{CO}) - \hat{\mu}_{\theta CO}(T_{\theta}, P_{\theta}, y_{\theta CO}) = RT_{\theta} \ln \frac{y_{CO}}{y_{\theta CO}} \quad (37)$$

with  $RT_{\theta} \ln y_{\theta CO}$  calculated from Eq. (36).

Since the right hand side of Eq. (36) does not contain  $y_{\theta CO}$ , it might be thought that the same result can be attained without the equilibrium constraint, just by specifying  $y_{\theta CO_2}$  and  $y_{\theta O_2}$ , and setting the environmental content of CO to 0. However, in this alternate approach, Eq. (36) is arrived at by considering a series of reversible steps, one of which inevitably involves chemical reaction which, for maximum work, can only take place in an equilibrium environment (van't Hoff box). Thus, it is the inclusion of the equilibrium reaction vessel rather than the neglect of the equilibrium constraint that characterizes this approach. In the present paper, on the other hand, the van't Hoff box is indistinguishable from (and belongs to) the environment. It is important to understand, however, that equilibrium must always be assumed when calculating maximum work.

## CONCLUSIONS

Availability contains all the thermodynamic information necessary for a Second Law analysis of efficiency. Exergy introduces no new thermodynamic information, but is useful in ranking process streams according to their potential for producing useful work. Hence, it is used to treat problems that require both economic and thermodynamic analysis [1, 2, 6, 7].

The following limitations, however, should be borne in mind:

1) An environment which is in stable thermodynamic equilibrium eliminates from consideration many realistic choices of environments whose components are not in equilibrium, but are prevented to react by kinetic barriers.

2) Although thermodynamic consistency is required in the selection of an equilibrium environment, such a choice, once consistency is satisfied, is completely arbitrary, and, moreover, the results are sensitive to the stable components selected.

3) The present analysis is limited to cases where the system under consideration exchanges heat with a single reservoir. □

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## NOMENCLATURE

$B$	availability (J)
$B'$	open system flow availability (J/mole)
$C_p$	molar heat capacity (J/mole·K)
$H$	stream molar enthalpy (J/mole)
$\dot{n}$	molar flow rate (mole/s)
$p$	partial pressure (N/m <sup>2</sup> )
$P$	pressure (N/m <sup>2</sup> )
$Q$	heat interaction (J)
$\dot{Q}$	rate of heat interaction (W)
$R$	gas constant (8.3144 J/mole·K)
$S$	stream molar entropy (J/mole·K)
$\underline{S}$	entropy (J/K)
$S^*$	created entropy (J/K)
$\dot{S}^*$	rate of entropy creation (W/K)
$T$	temperature (K)
$U$	energy (J)
$V$	volume (m <sup>3</sup> )
$W$	work interaction (J)
$\dot{W}$	rate of work interaction (W)
$X$	defined in text
$y$	mole fraction
$Z$	compressibility factor
$\eta$	Carnot efficiency
$\eta_{ex}$	exergetic efficiency
$\nu$	stoichiometric coefficient
$\psi$	exergy (J/mole)
$\mu^o$	molar free energy of formation at $T_o$ and $P_o$ (J/mole)
$\hat{\mu}$	component chemical potential in mixture (J/mole)

## Subscripts

1	refers to boundary shown in Fig. 1.a or exergy boundary
$e$	entering stream
$f$	final state
$i$	initial state
$j$	jth component
$l$	leaving stream
$r$	heat reservoir
$s$	system
$o$	environment conditions ( $T_o$ , $P_o$ , $y_{jo}$ )
-	extensive property

## Superscripts

-	partial molar property
$o$	standard conditions

# PROCESS DESIGN IN PROCESS CONTROL EDUCATION\*

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IN THE SPRING OF 1981, the author started teaching a process control course at Colorado State University. It was realized at that time that most universities taught the course following certain text books and that the course contents usually did not give an overall idea on how to integrate the concepts of process control into the overall process design. Dr. Morari (Wisconsin) and Dr. Stephanopoulos (Minnesota) [1] have advocated the need for integrating process control into the overall plant design. However, their ideas are too detailed and are beyond the scope of an undergraduate curriculum. Recently, Prassinos, McAvoy, and Bristol [2] presented some ideas about understanding complex control structures. However, none of these schemes have been classroom tested in any undergraduate program. The course at CSU was thus designed to expose students to the complexities of designing an instrumentation and control system for the overall plant. It was recognized that this would be a tremendous undertaking by

Presented at the poster session of the 1982 ASEE Summer School for Chemical Engineering Faculty at Santa Barbara, CA.

**TABLE 1. Semester Design Project**

## INSTRUMENTATION/CONTROL OF OLEFINS PLANT

The accompanying brochure describes the C-E Lummus process for manufacturing olefins. Flowsheets and material and energy balance information are provided in the brochure. The following are the purposes of the project:

1. Identify the control variables, manipulative variables, and the disturbances for individual equipment. Pair the possible control and manipulative variables.
2. Get approximate models for each system. Obtain the parameters of the models wherever possible.
3. Design control strategies for all the operations. Add safety features and information-oriented data collection systems when necessary.
4. Get rough estimates of the cost of the overall instrumentation of the plant.

The experience of the author is that students should be taught process control from the overall plant design concept. They should be exposed to the complexities and interconnections of different process units.

students who were seemingly unaware of the difficulties that could be encountered in such a project.

### PROJECT FORMAT

The students were divided into groups of two or three and were given the whole semester to complete the project. Table 1 shows the type of information (besides the flowsheet [Fig. 1]) that was given to the students.

In 1981, students designed an overall control system for the sodium dodecylbenzene sulfonate plant [3]. In 1982, the students designed an instrumentation and control system for an olefins plant. This was a C-E Lummus plant [4]. Typically, students were given flowsheets and some mass and energy balance information. They were taught how to select manipulative and control variables (using relative gain array). They were asked to make simplifying assumptions, where needed, to arrive at a steady state model of the individual unit operations. Where possible, they obtained dynamic models. They had to select the appropriate control schemes for individual unit operations, with particular emphasis on the possibility of reducing interactions between the loops (decoupling control). They had to design feed-forward controllers if appropriate dynamic or steady state models were available, to guard against disturbances. Then students had to identify the safety features of the plant and design proper instrumentations (like override control, safety alarm) to alleviate the safety problems. They had to draw a P&ID diagram for the overall system. The students were given instrument catalogs from which to select their instrument hardware (including computer systems). After selecting the appropriate hardware, they contacted the instrument vendors to get the unit prices. They finally calculated the cost

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of total instrumentation and control which was compared with that obtained using plant design texts [3].

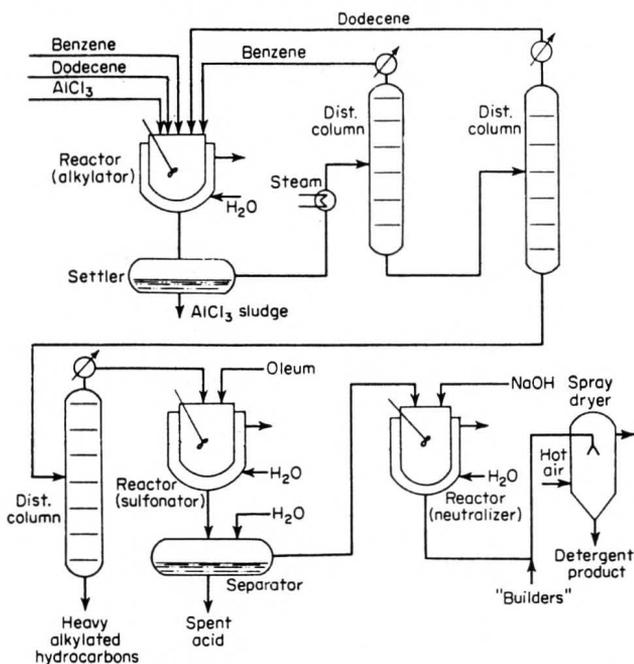
## DISCUSSION

### Accomplishments

- Students were able to apply the concepts learned in the "structured lectures" to a "real" plant.
- Students realized that in real life the instrumentation and control problems were not as simple as given in most of the texts.
- Students learned the practical aspects of looking up information in the vendor's catalog and of becoming familiar with the present state of the art as far as the availability of different instruments is concerned.
- Students learned to make simplifying assumptions to arrive at different models.
- Students learned about the possibility of application of advanced control techniques in the overall design of the plant.
- The experience gave the students a broader outlook on the design aspects of a plant.

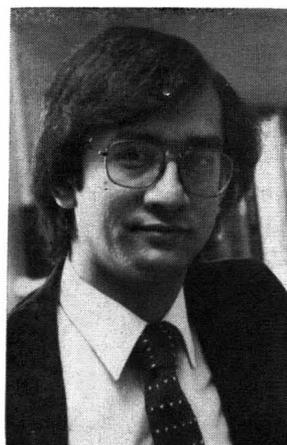
### Shortcomings

- Since the department of chemical engineering at CSU is new, it does not have "canned" computer programs to generate steady state and dynamic models of the unit processes.
- It was difficult to get the necessary information from the companies about the processes (C-E Lummus was



**FIGURE 1. Flow diagram for the manufacture of sodium dodecylbenzene sulfonate.\* Students designed the overall instrumentation and control system for this plant.**

\*Reprinted with permission of McGraw-Hill Book Company from *Plant Design and Economics for Chemical Engineers*, 3rd Edition, 1980, by M. Peters and K. D. Timmerhaus; page 22.



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reluctant to provide any more information about their plant than was already available in the literature).

- Students found it difficult to talk to some vendors, mainly because they were not actual customers. Students often did not have enough process information to all the questions the vendors asked them.

## CONCLUSION

The experience of the author is that students should be taught process control from the overall plant design concept. They should be exposed to the complexities and interconnections of different process units. As far as the author is aware, no textbook currently deals with this aspect. The industry should provide information about some "typical" plants so that students can arrive at simplified models. Students should have access to computer programs to obtain simplified models of the different unit processes and should be exposed to catalogs published by instrument vendors. The experience at CSU in trying to teach the concept discussed above has been reasonably successful. □

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# HOW WE MAKE MASS TRANSFER SEEM DIFFICULT

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MASS TRANSFER IS ONE of the few subjects taught only in chemical engineering. It is taught because it is important in the chemical process industries, basic to such operations as gas treating, liquid-liquid extraction, catalyst effectiveness, and cooling tower design. Fluid mechanics is, of course, taught in chemical engineering, but it is also carefully covered in civil engineering and in applied physics. Heat transfer is also taught in mechanical engineering, and thermodynamics is a core course in chemistry, just as it is in chemical engineering. However, mass transfer is taught in detail only in chemical engineering, and as such, is a unique focus of our profession.

I have no trouble explaining mass transfer at neighborhood parties. Over the years, I have learned to dread the social question, "What do you do, Ed?" If I answer, "I teach chemical engineering," the conversation switches to cars or sports. If I say, "I teach mass transfer," I get the response, "What on earth is mass transfer?" After I reassure my listener that mass transfer has nothing to do with the Teamsters, I can generally give a good brief answer.

However, most students think mass transfer is difficult, much harder than fluid mechanics or chemical thermodynamics. This is not true: mass transfer is easier. To prove this to yourself, try explaining a mass flux, a momentum flux, and a chemical potential at that same neighborhood party. Explaining the mass flux is easy: it is the mass transferred per area per time. Explaining the momentum flux is harder: no non-engineer will easily accept "the flux of y-momentum engendered

**I have found that the best way to overcome the carelessness in defining a system is a lot of drill on simple problems. I don't devote a single lecture exclusively to this, but try to sprinkle simple examples throughout the course.**

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by z-motion." Explaining the chemical potential is almost impossible: if it were not, there would not be such a glut of thermodynamics books.

But if mass transfer is easy, why do students think that it's hard? I believe it's because you and I teach it badly. We take a relatively simple subject and make it a nearly incomprehensible tangle of subscripts, superscripts, unit conversions, dimensionless correlations, correction factors, archaic graphs, and turgidly-written textbooks. We make a mess of it, so students think it's hard.

I think we should stop this tangled teaching, stop making students hate this cornerstone of our profession. In this paper, I have suggested three changes by which we may begin. First, we need to spend more time on simple problems which use a single, simple definition of mass transfer coefficients. Second, we need to use a different approach for describing analogies between mass, heat, and momentum transfer. Finally, we need a more coordinated approach for problems of diffusion and chemical reaction. Each of these changes is discussed in more detail below.

## SIMPLE PROBLEMS (for Undergraduate Courses)

Undergraduates have the same problems with simple mass transfer problems as they do in

thermodynamics: they define the system carelessly and they get the units fouled up. We all do this. When I presented this material at the ASEE summer school, the professors present made the same mistakes. I do, too.

I have found that the best way to overcome the carelessness in defining a system is a lot of drill on simple problems. I don't devote a single lecture exclusively to this, but try to sprinkle simple examples throughout the course. In this, I always choose problems in dilute solution, for these are basic. Extensions to concentrated solution can wait until these basics are mastered.

Three problems which I find useful in introducing the idea of a mass transfer coefficient are given in the Appendix. Try to solve at least one without looking at the solutions. They are easy, but you can't depend on having taught them before. Problems like these humble me, making me more sympathetic with my students' difficulties.

The three problems in the Appendix use a common definition of the mass transfer coefficient  $k$ , given by

$$N_1 = k\Delta c_1 = \left(\frac{D}{l}\right)\Delta c_1 \quad (1)$$

where  $N_1$  is the flux,  $\Delta c_1$  is the concentration difference,  $D$  is a diffusion coefficient, and  $l$  is a characteristic distance, sometimes called a "film thickness." I know that this distance is hypothetical and that it depends on the diffusion coefficient. Still, I find its use a tremendous advantage for two reasons. First, it establishes a clear connection between mass transfer and diffusion, one which

**I think we should stop this tangled teaching, stop making students hate this cornerstone of our profession. In this paper I have suggested three changes . . .**

the students easily remember. Second, it avoids the curse of units, which is a chief reason that mass transfer seems hard.

To illustrate this curse of units, compare the definition of the mass transfer coefficient in Eq. (1) with the other common definitions summarized in Table 1. Obviously, the units for  $k$  vary widely because the units used for concentration vary widely. This variation confuses students, clouding the physical meaning of the problem. Moreover, it is unnecessary. It is as if we wrote the ideal gas law as

$$pV = nT \quad (2)$$

Then we would describe the temperature  $T$  not only as  $^{\circ}\text{K}$  and  $^{\circ}\text{R}$  but as ( $l\cdot\text{atm}/\text{gmol}$ ), as ( $\text{kJ}/\text{kgmol}$ ), as ( $\text{psia}\cdot\text{ft}^3/\text{lbmol}$ ), as ( $\text{m}^3\cdot\text{Pa}/\text{kgmol}$ ). Such a description would compromise any physical intuition which students had about the meaning of temperature. In the same way, if we use the plethora of mass transfer coefficients in Table 1, we obscure the student's intuition about mass transfer.

#### ANALOGIES (for Undergraduate Courses)

Most undergraduate courses on transport processes discuss fluid mechanics first, then describe

**TABLE 1**  
**Common Definitions of Mass Transfer Coefficients\***

Basic Equation	Typical Units of $k^{**}$	Remarks
$N_1 = k\Delta c_1$	cm/sec	Common in the older literature; best because of its simple physical significance (Welty et al. 1969; Fahien, 1983).
$N_1 = k'\Delta p_1$	mol/cm <sup>2</sup> sec atm	Common for gas absorption; equivalent forms occur in biological problems (Sherwood et al., 1979; McCabe and Smith, 1975; Treybal, 1980).
$N_1 = k''\Delta x_1$	mol/cm <sup>2</sup> sec	Preferred for some theoretical calculations, especially in gases (Bennett & Myers, 1974; Geankoplis, 1978; Edwards et al., 1979).
$N_1 = k''' \Delta c_1 + c_1 v$	cm/sec	Used in an effort to include diffusion-induced convection in concentrated solutions (Bird, et al., 1960).

\*In this table, the interfacial flux  $N_1$  is defined as mol/L<sup>2</sup>t and the concentration  $c_1$  as mol/L<sup>3</sup>. Parallel definitions where  $N_1$  is in terms of M/L<sup>3</sup> are easily developed. Definitions mixing moles and mass are infrequently used.

\*\*For a gas of constant molar concentration  $c$ ,  $k = RTk' = k''/c$ . For a dilute liquid solution  $k = (\bar{M}_2 H/\rho)k' = (\bar{M}_2/\rho)k''$ , where  $\bar{M}_2$  is the molecular weight of the solvent,  $H$  is Henry's law constant of the solute and  $\rho$  is the solution density.

heat transfer, and conclude with mass transfer. These courses sensibly outline analogies between these processes, and conclude with a gaggle of dimensionless groups codifying the analogies. This often confuses all but the most mathematically adroit students.

The usual way in which the analogies are taught may be summarized as follows. First, diffusion in one dimension is described by Fick's law

$$-j_1 = D \frac{dc_1}{dz} \quad (3)$$

where  $D$  is the diffusion coefficient. If this diffusion takes place into a semi-infinite slab, the concentration profile is

$$\frac{c_1 - c_{10}}{c_{1\infty} - c_{10}} = \operatorname{erf} z / \sqrt{4Dt} \quad (4)$$

where  $c_{10}$  and  $c_{1\infty}$  are the concentrations at the slab's surface and far within the slab, respective-

**... we professors draw the analogy between mass, heat, and momentum transfer. If each process is subject to mathematically equivalent boundary conditions, then each leads to results of the same mathematical form.**

ly. Similarly, thermal conduction is described by Fourier's law

$$-q = k \frac{dT}{dz} \quad (5)$$

where  $k$  is the thermal conductivity. If conduction takes place into a similar semi-infinite slab, the temperature profile is

$$\frac{T - T_0}{T_\infty - T_0} = \operatorname{erf} z / \sqrt{4\alpha t} \quad (6)$$

where  $\alpha (= k/\rho C_p)$  is the thermal diffusivity and  $T_0$  and  $T_\infty$  are the temperatures of the surface of the slab and far within the slab, respectively. Finally, momentum transport follows Newton's law

$$-\tau = \mu \frac{dv}{dz} \quad (7)$$

where  $\tau$  is the momentum flux or the shear stress and  $\mu$  is the viscosity. If a flat plate is suddenly moved in an initially stagnant fluid, the velocity  $v$  of the fluid is

$$\frac{v - V}{0 - V} = \operatorname{erf} z / \sqrt{4\nu t} \quad (8)$$

where the plate's velocity is  $V$ , the fluid's velocity

far from the plate is zero, and the fluid's kinematic viscosity is  $\nu (= \mu/\rho)$ .

At this point, we professors draw the analogy between mass, heat, and momentum transfer. If each process is subject to mathematically equivalent boundary conditions, then each leads to results of the same mathematical form. Many say this is a more intimidating way: each process depends on combining a linear constitutive equation and a conservation relation to yield mathematically congruent results. The phenomenological coefficients of diffusion ( $D$ ), of thermal conductivity ( $k$ ), and of viscosity ( $\mu$ ) are thus analogous.

Many students find this conventional analogy confusing. Sure, Eqs. (3), (5), and (7) all say a flux varies with a first derivative. Sure, Eqs. (4), (6), and (8) all have an error function in them. But  $D$ ,  $k$ , and  $\mu$  do not have the same physical dimensions. Moreover,  $D$  appears in both Eqs. (3) and (4), but  $k$  in Eq. (5) must be replaced by  $\alpha$  in Eq. (6). The viscosity  $\mu$  in Eq. (7) is replaced by the kinematic viscosity  $\nu$  in Eq. (8). These changes frustrate many students, and undercut any value which the analogies have.

The source of confusion stems from the ways in which the basic laws are written. In Fick's law (Eq. 3), the molar flux varies with the gradient in moles per volume. To be analogous, the energy flux  $q$  should be proportional to the gradient of the energy per volume ( $\rho C_p T$ ). In other words, Eq. (5) should be rewritten as

$$-q = \frac{k}{\rho C_p} \frac{d}{dz} (\rho C_p T) = \alpha \frac{d}{dz} (\rho C_p T) \quad (9)$$

Now mass and heat transfer are truly analogous. Just as Eq. (4) follows from Eq. (3), so Eq. (6) follows from Eq. (9). Similarly, Newton's law for momentum transport can also be rewritten so that the momentum flux is proportional to the gradient of the momentum per volume ( $\rho v$ )

$$-\tau = \frac{\mu}{\rho} \frac{d}{dz} (\rho v) = \nu \frac{d}{dz} (\rho v) \quad (10)$$

This new form leads directly to Eq. (8).

Just as the fundamental laws for mass, heat, and momentum transfer can be made more parallel, so can expressions for mass transfer coefficients and heat transfer coefficients. The interfacial mass flux already varies with the difference in moles per volume.

$$N_1 = k \Delta c_1 \quad (11)$$

The interfacial heat flux must be modified so that the energy flux varies with the energy difference

**TABLE 2**  
**Analogies Between Processes Are Clearer With Flux Equations In An Uncommon, But Dimensionally Analogous Form.**

	MASS TRANSFER		HEAT TRANSFER		MOMENTUM TRANSFER	
	Common Form	Analogous Form	Common Form	Analogous Form	Common Form	Analogous Form
<b>Variable</b>	concentration $c_1$	moles/volume $c_1$	temperature $T$	energy/volume $\rho C_p T$	velocity $v$	momentum/ volume $\rho v$
<b>Physical Property</b>	diffusion coef. $D$ (Eq. 3)	diffusion coef. $D$ (Eq. 3)	thermal conduct. $k$ (Eq. 4)	thermal dif. $\alpha$ (Eq. 9)	viscosity $\mu$ (Eq. 7)	kinematic visc. $\nu$ (Eq. 10)
<b>Transfer Coefficient</b>	mass transfer coefficient $k$ (Eq. 11)	mass transfer coefficient $k$ (Eq. 11)	heat transfer coefficient $h$ (Eq. 12)	$(h/\rho C_p)$ (Eq. 12)	friction factor $f$ (Eq. 13)	$(fv/2)$ (Eq. 13)
<b>Dimensionless Groups</b>	Schmidt number $\mu/\rho D$	Schmidt number $\nu/D$	Prandlt number $\mu C_p/k$	Prandlt number $\nu/\alpha$		
	Sherwood number $kd/D$	Stanton number $k/v$	Nusselt number $hd/k$	Stanton number $(h/\rho C_p)/v$		
	Lewis number $k/(\rho C_p D)$	Lewis number $\alpha/D$				

per volume

$$q \Big|_{z=0} = h\Delta T = \frac{h}{\rho C_p} \Delta(\rho C_p T) \quad (12)$$

Thus the mass transfer coefficient  $k$  corresponds less directly to the heat transfer coefficient  $h$  than to the quantity  $h/\rho C_p$ . The appropriate parallel for momentum transfer is the dimensionless friction factor  $f$ , defined as

$$\tau = f \left( \frac{1}{2} \rho v^2 \right) = \left( \frac{fv}{2} \right) (\rho v - 0) \quad (13)$$

Thus  $(fv/2)$  is like  $k$  and  $(h/\rho C_p)$ .

When these equations are written in these parallel forms, they automatically suggest the most common dimensionless groups. For example, the ratio of coefficients in Eqs. (3) and (10) is  $\nu/D$ , the Schmidt number. The ratio of coefficients in Eqs. (11) and (13) is  $(k/v)(2/f)$ . Because  $(2/f)$  is itself dimensionless, this is equivalent to  $k/v$ , the Stanton number.

These analogies, summarized in Table 2, have made my teaching of mass transfer more effective. I can see the light dawn on dozens of student faces: that quite pause, and then a slow "Oh, I see . . ." Try this yourself the next time you lecture on a problem like the wet bulb thermometer.

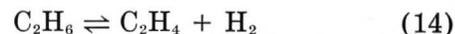
#### CHEMICAL REACTIONS (for Graduate Courses)

A third area in which we can improve our teaching concerns the coupling of mass transfer and chemical reaction. I have had trouble teaching

this material (even to graduate students) for two reasons. The first is that, in most curricula, courses in transport phenomena are very separate from those in chemical kinetics and reactor design. I could do a better job if the mass transfer and reaction courses were more completely integrated. We haven't solved this problem.

The second reason that mass transfer and reaction are poorly taught, which I struggle to avoid, hinges on the distinction between heterogeneous and homogeneous chemical reactions. I make this distinction either in chemical terms or in mathematical ones, and I often forget to tell the students which terms I am using.

I can best illustrate this by an example. Imagine we are discussing that old warhorse of reaction kinetics, ethane dehydrogenation on platinum. The overall reaction is simple.



My modeling of the reaction can be more subtle. If the platinum is a simple crystal, I treat this reaction as heterogeneous, occurring on the surface of the crystal. This is the route taken in chemistry courses or at the start of reaction engineering courses where mechanisms matter. However, if the catalyst is dispersed in a porous support, I discuss catalyst effectiveness factors as if the reaction were homogeneous. The chemistry is the same, but my mathematical treatment changes.

To look at this in more detail, consider the key

Continued on page 149.

# THE TWO LOST-WORK STATEMENTS AND THE COMBINED FIRST- AND SECOND-LAW STATEMENT

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ALL OF THE FUNDAMENTAL thermodynamic development for computing the reversible work of processes was apparently known and published by 1903. Therefore, this paper and similar papers discuss only the question of which of the many possible approaches for applying thermodynamic analysis to various kinds of processes is easiest to teach, easiest to understand, and most likely to be applied correctly by the average engineer.

## WHY USE LOST WORK?

This paper is largely about the "lost work" approach, which has some advantages over other approaches. The first advantage of lost work is that it has a very high intuitive content. This was the reason it was first introduced. In many important cases, it is exactly equal to the work converted to friction heating.

The second advantage is that the sum of the lost work and the work actually performed is equal to the reversible work

$$dW_{\text{rev}} = dW + dLW \quad (1)$$

This reversible work has a character quite different from either the actual work or the lost work, which are both path functions whose value depends upon the path followed going from the initial to the final state. However, the reversible work, their sum, is a state function; its value depends only on the initial and final states of the system and the heat and matter flows across the system boundaries; it is independent of the path actually followed.

The third advantage of the lost work is that it can be used to make direct computations of the reversible work, the lost work, and the thermodynamic efficiency of any process.

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**This paper is largely about the "lost work" approach, which has some advantages over other approaches. The first advantage . . . is that it has a very high intuitive content. . . . In many important cases, it is exactly equal to the work converted to friction heating.**

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## WHAT IS THE ALTERNATIVE?

If one does not wish to use the lost-work approach to the second-law analysis of chemical processes, the alternative is the availability-exergy-essergy approach. Another paper [5] attempts to show that, although the other approach has many advocates and is widely used, it is generally not as suitable for the analysis of chemical engineering processes as is the lost-work approach.

## WHY ISN'T LOST WORK USED?

A principal purpose of this paper is to show that lost work has not been widely used because there exist in the literature two very different quantities that both go by the same name, "lost work." For reasons that will be clear later, we call these two definitions  $LW_m$  (for mechanical lost work) and  $LW_t$  (for thermodynamic lost work). The existence of these two different quantities has led to confusion and misapplication of the lost work with the result that the lost work has not been utilized as widely as it should have been.

Although the concept of "wasted work," "dissipated work," "useless work," or other such terms was present in the literature for many years and the correct theoretical basis for the application of the concept was shown by Gibbs in 1876 [7], as far as we know, the first to use the term "lost work" in the chemical engineering literature and in chemical engineering textbooks and handbooks was G. G. Brown [3]. As far as we can tell, he formulated it independently of others who may have had similar ideas before him. He then worked with Sliepcevich [2] and Martin [10] who extended and developed the idea. Several authors adopted



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lost work and used Brown's formulation in textbooks [1, 16, 17].

Meanwhile, Van Ness developed a different version of the lost work [14, 15]. His version appears in his thermodynamics textbook with Smith and in the 5th Edition of *Perry's Handbook*. On the other hand, Brown and Sliepcevich's version appears in the 3rd and 4th editions of *Perry's Handbook*. To our knowledge, no one has previously shown that between the 4th and 5th editions of *Perry's Handbook*, the fundamental thermodynamic orientation toward lost work changed. We believe that this change is significant and should be known and understood by chemical engineers.

Turning now from the history of the two concepts, let us contrast them by means of discussion and Table 1.

### THE TWO LOST-WORK CONCEPTS

We begin by defining two auxiliary quantities,

$$\text{Work converted to heat (or to internal energy)} = \text{WCTH} \quad (2)$$

$$\text{Work to restore system} = \text{WTRS} \quad (3)$$

The first of these (WCTH) is the amount of shaft work, falling weight work, or its equivalent ( $\int PdV$  work, electrical work, decrease in kinetic or potential energy, and decrease in magnetic or chemical or diffusional potential to do work) that is converted to heat or to internal energy. This is equivalent to mechanical, frictional rubbing as in a brake.

The second of these (WTRS) is the amount of work that must be supplied to restore a system to its original conditions after some process of change has occurred in the system. The restoration process exchanges heat only with the infinite surroundings at  $T_0$ .

The quantities WCTH and WTRS are not *in general* the same; they are the same *if and only if* the system considered is uniformly isothermal at the temperature,  $T_0$ , of the infinite surroundings.

The earliest published reference to the lost work that we have found is in Brown et al [3]

In any process the increase in internal energy due

to heat effects  $\int_1^2 TdS$  is equal to the sum of the heat

absorbed from the surroundings and all other energy dissipated into heat effects within the system due to irreversibilities such as overcoming friction occurring in the process,

$$\int_1^2 TdS = q + (lw) \quad (58)$$

where  $lw =$  "lost work," energy that could have done

**TABLE 1**  
Comparison of the Two Lost-Work Definitions

	LW <sub>m</sub> Mechanical Lost Work	LW <sub>t</sub> Thermodynamic Lost Work
Definition	LW <sub>m</sub> = WCTH	LW <sub>t</sub> = WTRS - W
Definition in terms of dS <sub>irr</sub>	dLW <sub>m</sub> = TdS <sub>irr</sub>	dLW <sub>t</sub> = T <sub>0</sub> dS <sub>irr</sub>
Unambiguously defined for non-isothermal systems?	NO	YES
Computable for an iso- thermal system without reference to surround- ings temperature?	YES	NO
Leads to a reversible work statement that is an unambiguous state function for all cases including non- isothermal cases?	NO	YES

... as far as we know,  
 the first to use the term "lost work" in  
 the chemical engineering literature and in chemical  
 engineering textbooks ... was G. G. Brown.

work but was dissipated in irreversibilities within the  
 flowing material.

Although Brown directed it at irreversibilities in  
 flowing streams, the concept of lost work given  
 above can, in principle, be applied to any type of  
 process.

This idea was expanded and placed in more  
 general form by Brown and Sliepcevich [2]

Lost Work. Because, as commonly used,  $\int TdS$  does  
 not differentiate between heat and loss of potential  
 energy, another expression ( $lw$ ) is used to designate all  
 potential work dissipated in overcoming resistances or  
 in irreversibilities or "lost work." It represents the  
 energy that might have been evident as work if it had  
 not been so dissipated. Accordingly

$$\int TdS = q + (lw) \quad (1)$$

The lost work defined in these two equations is  
 equivalent to

$$LW = WCTH \quad (4)$$

We may also utilize the formulation of the  
 second law shown by Denbigh [6] (attributed by  
 him to de Donder), in which a term is introduced  
 for the irreversible entropy production. In it, for a  
 closed system, we would have

$$dS = dQ/T + dS_{irr} \quad (5)$$

Comparing Eq. (5) with the definition of  $lw$  given  
 in the two preceding quotes, we find that Brown's  
 definition of lost work is equivalent to

$$d(LW) = TdS_{irr} \quad (6)$$

In Table 1, we have called this definition of the lost  
 work  $LW_m$ ; i.e., mechanical lost work. Eqs. (4)  
 and (6) are shown as the first two entries of Table  
 1 under  $LW_m$ .

The other definition of lost work (which we  
 call  $LW_t$ , thermodynamic lost work, and shown  
 as a column with that heading in Table 1) was  
 also apparently first defined by Brown and  
 Sliepcevich [2]. In that article, they followed their  
 basic definition of the lost work quoted above with  
 two subcases. In an isothermal subcase, they write  
 their entropy balance with a quantity  $(lw)_T$ . In  
 the other subcase, for systems that exchange heat

only with the surroundings at  $T_o$ , they write their  
 entropy balance with a quantity  $(lw)_o$ . They do  
 not in any way remark in that article (or any other  
 subsequent publication we have found) that  $(lw)_o$   
 is not the same quantity as  $(lw)_T$ . However, if we  
 follow their examples, we find that  $(lw)_T$  is the lost  
 work in their basic defining equation while, substi-  
 tuting their  $(lw)_o$  into Eq. (5), we see that

$$d(lw)_o = T_o dS_{irr} \quad (7)$$

or

$$(lw)_o = \frac{T_o}{T} (lw)_T \quad (8)$$

(In the terms used in this paper,  $LW_t = (T_o/T)LW_m$ .)

The second definition of lost work ( $(lw)_o =$   
 $LW_t$ ) was arrived at independently by Van Ness.  
 He informs us that his development was totally  
 independent of that of Brown, Sliepcevich, and  
 Martin. In 1956, Van Ness published his first paper  
 on the topic, in which he defined the lost work as  
 minus the value in Eq. (7). (The choice of whether  
 to make the lost work positive or negative is  
 arbitrary; Brown makes it positive, Van Ness  
 originally made it negative, then switched and  
 made it positive [12]. We use the positive value  
 here.)

In his 1956 article [14], Van Ness arrived at  
 his definition by considering the reversible work  
 necessary to restore a system to its original con-  
 dition after some change has occurred in the  
 system, allowing heat exchange with the sur-  
 roundings only at  $T_o$  and subtracting the work  
 done by the system during that change. The proofs  
 are shown there that

$$LW_t = WTRS - W \quad (9)$$

Thus, we show in Table 1 this property of  $LW_t$ .

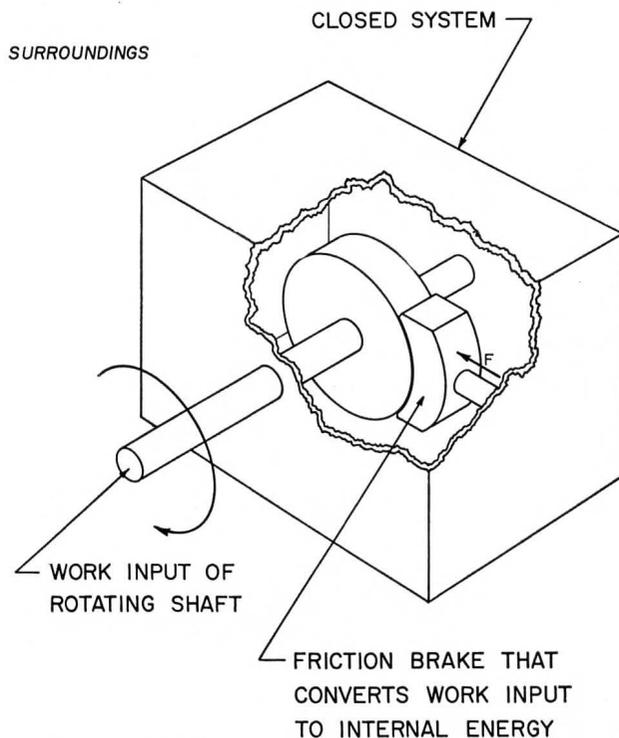
At this point, the application of the two defini-  
 tions to a simple example may make their differ-  
 ence clear. Consider a system consisting of an  
 isobaric, adiabatic container filled with a vapor-  
 liquid mixture of helium at its normal boiling  
 point of 4°K. Work added to the system by means  
 of a friction brake, as shown in Fig. 1, is converted  
 to internal energy of the helium. The irreversible  
 entropy increase of the system is equal to the work  
 input ( $WCTH$ ) divided by the system tempera-  
 ture,  $T_{sys}$ , where the conversion takes place. But is  
 the *work input* the same as the *lost work*? Accord-  
 ing to the definition proposed by Brown (Eq. 4),  
 it is the same; work input converted to friction  
 heat equals lost work.

Suppose we decide that the lost work is not simply the work input converted to internal energy but also the amount of reversible work that would be required to restore the system to its original state, as apparently first suggested by Van Ness [14]. To restore the system, suppose we use a refrigerator of some ideal type to extract heat from the system in an amount equal to the increase in internal energy and reject heat to the surroundings (assumed to be infinite) at temperature  $T_o$ . By straightforward application of the theory of Carnot refrigerators, we have

$$WTRS = LW_m \left( \frac{T_o - T_{sys}}{T_{sys}} \right) \quad (10)$$

Unlimited amounts of heat may be rejected to or absorbed from the infinite surroundings at  $T_o$ . Normally, the surroundings temperature can be taken as that of the nearest body of water (for example, a river, lake, or ocean) or the water temperature that can be easily reached in atmospheric cooling towers or atmospheric air. Assuming that  $T_o$  is  $25^\circ\text{C}$  ( $298^\circ\text{K}$ ), from Eq. (10), the reversible work to restore the helium system is  $(298 - 4) / 4$  or 73.5 times the work input converted to internal energy.

For the system in Fig. 1, Brown defined the



**FIGURE 1. Friction brake to convert work to internal energy.**

lost work as the work input to the system, which is equal to  $LW_m$ . From a practical engineering viewpoint, we believe that this definition is incorrect. If the work input is converted to internal energy of helium, thus causing some of it to vaporize isobarically at its normal boiling point, then somewhere else in the world some helium liquefier is doing the work to remove that same amount of heat to supply us with liquid helium. That helium liquefier may be part of our plant or that of our

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**To our knowledge, no one has previously shown that between the 4th and 5th editions of Perry's Handbook, the fundamental thermodynamic orientation toward lost work changed.**

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liquid helium supplier; but, either way, we must pay for the work it does. Thus, in practical terms, the real loss is not only the work converted to internal energy but also the reversible work required to offset this irreversible conversion. Therefore, we assert that the practical definition of the lost work is that definition apparently first used by Brown and Sliepcevich [2], which they called  $(lw)_o$ , but which they apparently never subsequently used and which was later independently introduced by Van Ness [14] and which we term the "thermodynamic lost work" ( $LW_t$ ), where, in general

$$LW_t = WTRS - W \quad (11)$$

In the particular case of the friction brake in helium,

$$LW_t = WTRS + LW_m \quad (12)$$

because  $LW_m$  is simply the negative of the thermodynamic work *produced* by the system. Combining Eqs. (10) and (12) to eliminate the  $WTRS$ , we obtain

$$LW_t = LW_m \frac{T_o}{T_{sys}} \quad (13)$$

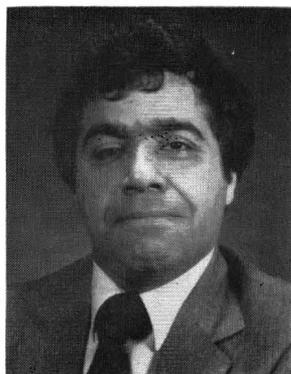
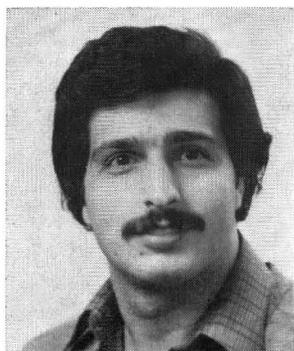
Why is  $LW_t$  not equal to  $WTRS$ ? If there is no exchange of work between the system and its surroundings during the irreversible process, then the  $W$  in Eq. (11) is zero, and  $LW_t = WTRS$ . But for cases in which the external work during the irreversible process is not zero, the  $W$  term is significant. We may see this by considering a general, irreversible process in a closed system that proceeds from State 1 to State 2. The work to restore the system to State 1, exchanging heat only with the surroundings at  $T_o$ , is independent of the ir-

Continued on page 146.

# TRAY DRYING OF SOLIDS

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**T**HE EXPERIMENT described in this paper is designed to expose the students to two topics: the principles of drying and simultaneous heat and mass transfer. Drying of solids is considered to occur in two stages, a constant rate period followed by a falling rate period. In the constant rate period, the rate of drying corresponds to the removal of water from the surface of the solid. The falling rate period corresponds to the removal of the water from the interior of the solid. The rate in either case is dependent on a number of factors. Some of these are the air wet and dry bulb temperatures, flow rate of air, the solids characteristics and the tray material.



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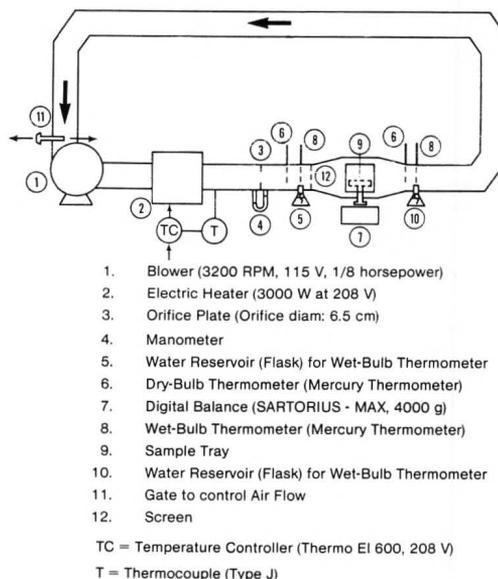


FIGURE 1. Schematic of experimental equipment.

## THEORY

Drying can be described in terms of gas mass-transfer and heat transfer coefficients. The rate of drying is given by

$$N_c = k_Y (Y_s - Y) = \frac{q}{\lambda_s} \quad (1)$$

where  $q$  is the total heat supplied by the gas stream to the solid and it is given by

$$q = h_c (T_g - T_s) + h_r (T_r - T_s) + U_k (T_g - T_s) \quad (2)$$

where  $h_c$ ,  $h_r$ ,  $U_k$  are the heat transfer coefficients for convection, radiation, and conduction, respectively. They are given by Treybal [1] as

$$h_c = 14.3 G^{0.8} \quad (3)$$

$$h_r = \epsilon \sigma (T_r^4 - T_s^4) / (T_r - T_s) \quad (4)$$

$$U_k = \left[ (1/h_c) (A/A_u) + (Z_m/k_m) (A/A_u) + (Z_s k/k_s) (A/A_m) \right]^{-1} \quad (5)$$

Making use of Eqs. (1) and (2), the relationship between  $T_s$  and  $Y_s$  becomes

$$\frac{(Y_s - Y)\lambda_s}{(h_c/k_y)} = \left(1 + \frac{U_k}{h_c}\right) (T_g - T_s) + \frac{h_r}{h_c} (T_r - T_s) \quad (6)$$

where  $(h_c/k_y)$  ratio is related to Lewis number,  $Le$ , and is given by Henry and Epstein [2] as

$$\frac{h_c}{k_y C_s} = \left(\frac{S_c}{Pr}\right)^{0.567} = Le^{0.567} \quad (7)$$

$C_s$  is the specific heat of saturated gas at  $T_s$ .

For an air-water system the Lewis number is approximately equal to unity. Eqs. (3) and (7) are used to evaluate  $h_c$  and  $k_y$ , respectively. Simultaneous iterative solution of Eq. (6) with the saturation humidity curve provides the solid surface temperature  $T_s$  and the corresponding value of the humidity,  $Y_s$ . Once  $Y_s$  is known, Eq. (1) can be used to calculate the theoretical drying rate,  $N_c$ . The absolute air humidity  $Y$  is measured experimentally from the dry and wet bulb temperatures.

## EQUIPMENT

A schematic diagram of the experimental set-up is shown in Fig. 1. It is a wind-tunnel type tray dryer designed to give a good control of air temperature and air flow rate. It consists of an air blower, a heater and an orifice plate in the air duct, and a tray sample mounted on a digital balance. The air flow rate is controlled by a gate in

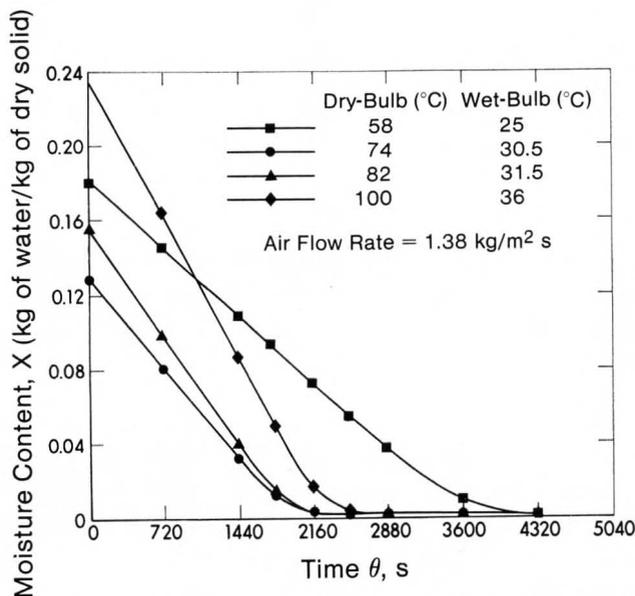


FIGURE 2. Variation of moisture content with time for different air temperatures.

**The reasonably good agreement  
in the calculated rate of drying and that  
observed experimentally makes students feel confident  
in applying engineering design correlations.**

the blower inlet line, and its flow rate is measured by a pre-calibrated orifice-meter. The temperature is controlled by a closed-loop on-off controller. Wet and dry bulb thermometers are placed at the inlet and outlet of the drying chamber. The wet-bulb temperature is measured by a mercury thermometer, with its bulb covered by a wick kept in a water reservoir. The water reservoir is attached to the bottom of the duct as shown in Fig. 1. This method of measuring the wet-bulb temperature was simple and inexpensive. However, this method was later replaced by humidity sensors to obtain more accurate and direct measurements.

The cross-section of the air duct is 0.12 m × 0.12 m and that of the drying chamber section containing sample tray is 0.185 m × 0.28 m. The sample tray is made of aluminum sheel metal having a thickness of 0.001 m and dimensions of 0.125 m × 0.16 m × 0.007 m.

## EXPERIMENTAL PROCEDURE

Two sets of experiments are performed: one set is at a constant air temperature and different air flow rates, and the other is at a constant air flow rate and different air temperatures. The drying material used is Ottawa-sand (35-48 Mesh). The tray sample is loaded with about 250 g of sand and placed over the balance in the drying chamber. The weight of the tray and the sand is recorded. When the desired conditions of temperature and air velocity are reached (about 10 min), the sample tray is removed and the sand is wetted to give a desired initial moisture content. A stop watch is started and the balance reading is taken. Subsequent balance readings are taken at about three minute intervals. Drying is assumed to be complete when at least three consecutive readings are unchanged. The wet/dry bulb temperatures at the inlet and outlet of the drying chamber and air flow rate are recorded at least three times during the course of a run to give average operating conditions.

The same procedure is repeated for other runs at different operating conditions. The range of the variables studied are: air flow rate, 1-1.5 kg/m<sup>2</sup>s;

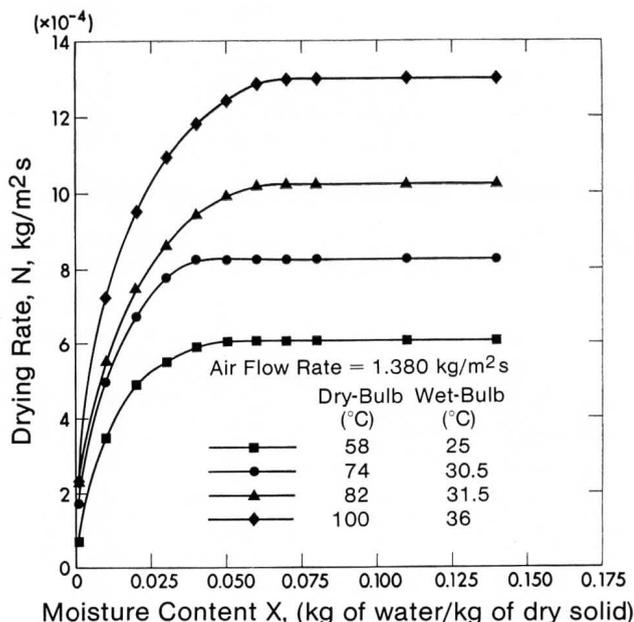


FIGURE 3. Variation of drying rate with moisture content for different air temperatures.

air temperature, 50-100°C; sand initial moisture, 15-20%.

## RESULTS AND DISCUSSION

From the measurement of the weight of the sand sample, the moisture content ( $X$ ) of the sample at different times is calculated. A typical plot of the variation of moisture content with time is shown in Fig. 2.

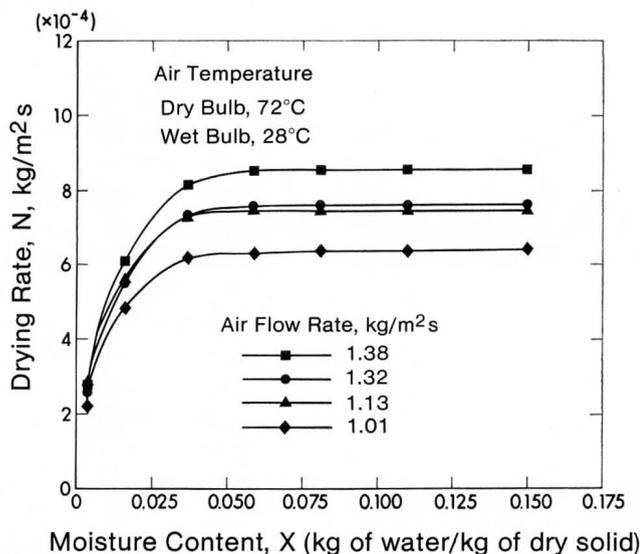


FIGURE 4. Variation of drying rate with moisture content for different air flow rates.

The drying rate is calculated from the relationship

$$N = -S \frac{dX}{d\theta} \cdot \frac{1}{A}$$

where the rate of change of the moisture content,  $dX/d\theta$ , is obtained from the slope of the curve  $X$  vs  $\theta$  of Fig. 2. The drying rate is then plotted against the moisture content. Figs. 3 and 4 show typical plots of the variation of the drying rate with moisture content at constant air flow rate and constant air temperature, respectively.

Fig. 5 gives a comparison of the constant drying rate,  $N_c$ , calculated using Eq. (1) with that experimentally measured. The agreement is within 20%, with the calculated values being consistently lower.

Since the variation of the latent heat of vaporization and that of the radiation heat transfer

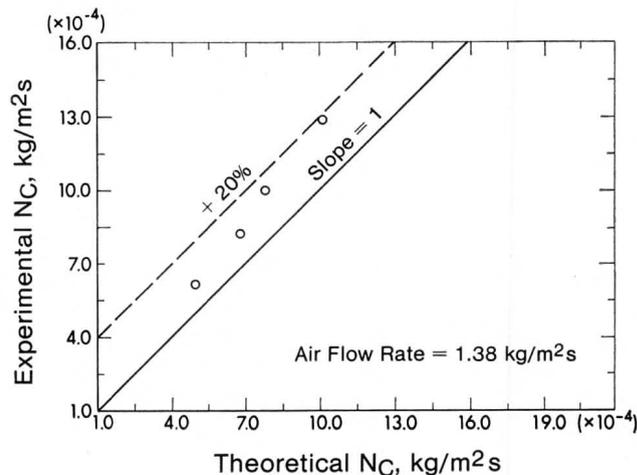


FIGURE 5. Comparison between experimental and theoretical drying rates at different air temperatures.

is fairly small for the range of temperature covered in this experiment, the overall drying rate  $N_c$  becomes directly proportional to the overall driving force  $T_g - T_s$ . Fig. 6 shows such a dependence.

The effect of air flow rate on drying rate during constant drying period is shown in Fig. 7. It shows that the constant drying rate,  $N_c$ , is proportional to  $G^{0.8}$ . The linear dependence of  $N_c$  on  $G^{0.8}$  is not surprising as the convective heat transfer is the major mode of transfer and the convective heat transfer coefficient,  $h_c$ , is proportional to  $G^{0.8}$  as given by Eq. (3).

## CONCLUSION

The drying experiment proposed here is useful in presenting the concept of simultaneous heat and mass transfer. The reasonably good agreement in the calculated rate of drying and that ob-

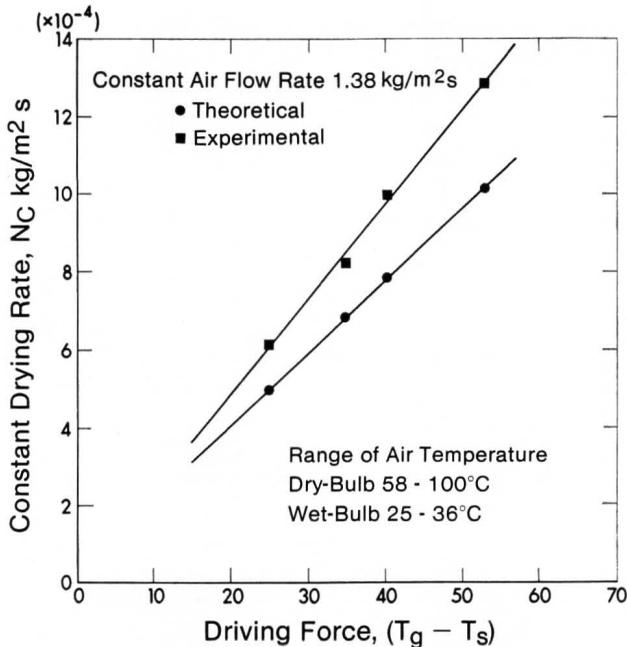


FIGURE 6. Effect of temperature driving force on drying rate at constant air flow rate.

served experimentally makes students feel confident in applying engineering design correlations. □

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2. Henry, H. C., and N. Epstein: *Can. J. Chem. Eng.*, 48, 595, 602, 609 (1970).

## NOMENCLATURE

A	Drying surface area [ $m^2$ ]
$A_u$	Nondrying surface area of drying solid [ $m^2$ ]
$A_m$	Average solid surface area [ $m^2$ ]
$C_s$	Saturated specific heat of the gas [J for mixture/kg (air) °C]
$C_p$	Specific heat [J/kg °C]
$D_{AB}$	Diffusivity [ $m^2/s$ ]
G	Mass velocity of gas [ $kg/m^2 \cdot s$ ]
$h_c$	Heat transfer coefficient for convection [ $w/m^2 \cdot K$ ]
$h_r$	Heat transfer coefficient for radiation [ $w/m^2 \cdot K$ ]
k	Thermal Conductivity of gas [ $w/m^2 \cdot K$ ]

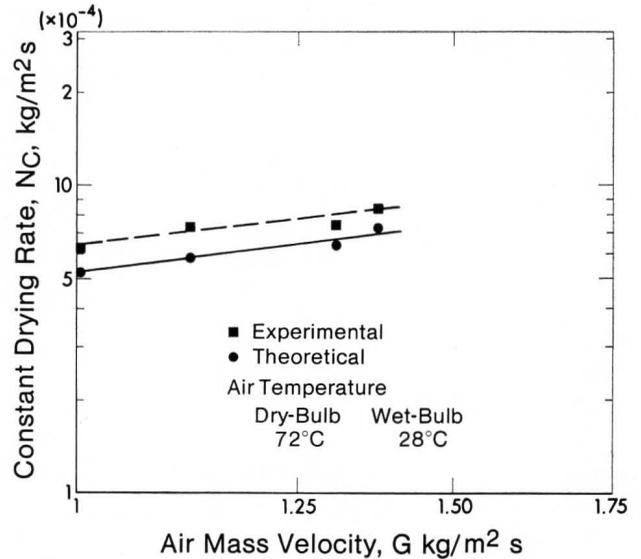


FIGURE 7. Effect of air velocity on drying rate at constant air temperature.

$k_s$	Thermal Conductivity of solid (sand) [ $w/m^2 \cdot K$ ]
$k_m$	Thermal conductivity of tray [ $w/m^2 \cdot K$ ]
$k_Y$	Gas phase mass transfer coefficient [ $kg \text{ dry air}/m^2 \cdot s$ ]
Le	Lewis number [ $Le = Sc/Pr$ ]
N	Drying rate [ $kg/m^2 \cdot s$ ]
$N_c$	Constant drying rate [ $kg/m^2 \cdot s$ ]
Pr	Prandtl number [ $Pr = C_p \mu/k$ ]
q	Total flux of heat received at the drying surface [ $w/m^2$ ]
$q_c$	Heat flux due to convection [ $w/m^2$ ]
$q_k$	Heat flux due to conduction [ $w/m^2$ ]
$q_r$	Heat flux due to radiation [ $w/m^2$ ]
S	Mass of dry solid (sand) [kg]
Sc	Schmidt number [ $Sc = \mu/\rho D_{AB}$ ]
$T_g$	Absolute temperature of gas (dry-bulb) [K]
$T_r$	Absolute temperature of radiating surface [K]
$T_s$	Absolute temperature of solid surface [K]
$U_k$	Overall heat transfer coefficient [ $w/m^2 \cdot K$ ]
X	Moisture content of a solid [kg of water/kg of dry solid]
Y	Absolute humidity [kg water vapor/kg dry air]
$Y_s$	Saturated humidity at surface of solid temperature [kg water vapor/kg dry air]
$Z_m$	Metal thickness [m]
$Z_s$	Sand thickness [m]

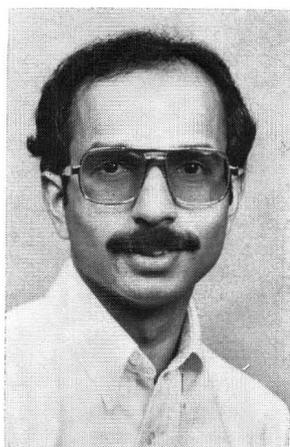
**Greek Symbols**

$\epsilon$	Emissivity of drying surface [dimensionless]
$\theta$	Time [s]
$\lambda_s$	Latent heat of vaporization at $T_s$ [J/kg]
$\sigma$	Stefan-Boltzman Constant $5.729 \times 10^{-8}$ [ $w/m^2 \cdot K^4$ ]
$\mu$	Viscosity [kg/m·s]
$\rho$	Density [ $kg/m^3$ ]

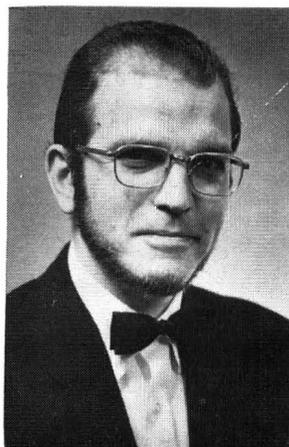
# A MICROCOMPUTER BASED LABORATORY FOR TEACHING COMPUTER PROCESS CONTROL

BABU JOSEPH AND DAVID ELLIOTT  
 Washington University  
 St. Louis, MO 63130

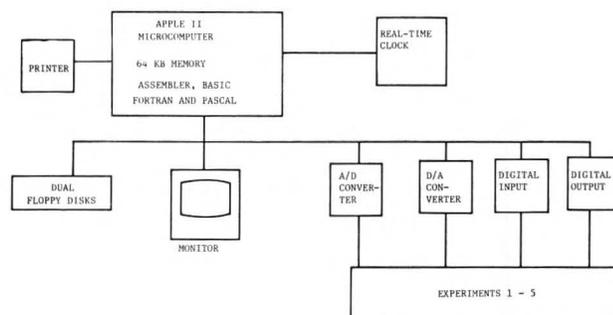
**M**OST SCHOOLS NOW REQUIRE undergraduate students in chemical engineering to take at least one course in process dynamics and control. The advent of the microcomputer has had a major impact in the instrumentation and control field, and this must be reflected in the curricula through added coverage of digital control systems and exposure to computer based data acquisition and control systems. In order to meet this demand, Washington University undertook the development



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**David L. Elliott** received his PhD in system science from UCLA in 1969 and has taught mathematical systems at Washington University since 1971. Besides microcomputer applications, he is interested in the geometric approach to nonlinear systems, stemming from his work in the 1960s on the attitude control of underwater vehicles (U.S. Naval Ocean Systems Center) and the identification of enzyme-kinetics models for blood coagulation. He has published papers on bilinear systems, nonlinear observers, and linearization of systems by coordinate and feedback transformations. He is an editor of *Mathematical System Theory* and a former editor of the IEEE Control Society Newsletter. (R)



**FIGURE 1. Computer system configuration.**

of a new laboratory course specifically designed to teach the principles of process data acquisition and control using digital computers. The structure of the laboratory and the course are discussed in this article.

## COMPUTER SYSTEM CONFIGURATION

A decision was made early in the development of the laboratory to provide as much exposure as possible to the computing hardware used without getting engrossed in computer system architecture. We finally decided on using a set of dedicated Apple microcomputers, primarily because of their low cost, availability of plug-in compatible modules for data acquisition, and their popularity as a general purpose personal computer. The students like having their "own machine" to work with. It is also fun to work with after a few basic commands have been mastered. Particularly attractive is the graphics capability which allows data or results to be represented graphically using a very small set of commands. It does not hurt to have a few video games which the students can play during off hours.

Although the Apple has a wide variety of languages that could be used, we selected Apple-soft, which is a floating point version of BASIC. Students who take the course have already been exposed to computers and we generally found that the students can be brought up to speed (including

the use of graphics) in about two laboratory sessions. These sessions generally involve stepping through the tutorial manuals rather quickly. Unlike the manuals written for large computer systems, these manuals are very well written and quite easy for the students to follow. An important advantage of an interpretive language like BASIC is the ease with which small programs are written, edited, and debugged. The students can write and use mostly their own programs and yet run the experiment within the time allocated.

In addition to the computer, a disk drive allows students to store their programs and data. Each student is issued a diskette for his exclusive use.

For converting the Apple to a data acquisition device, two 'cards' which plug into the mother board of the Apple were added. One is a real-time clock which enables timing of the data acquisition. The other is an A-D/D-A manufactured by Mountain Computer which allows sixteen channels each of analog-to-digital and digital-to-analog con-

. . . Washington University undertook the development of a new laboratory course specifically designed to teach the principles of process data acquisition and control using digital computers. The structure of the laboratory and the course are discussed in this article.

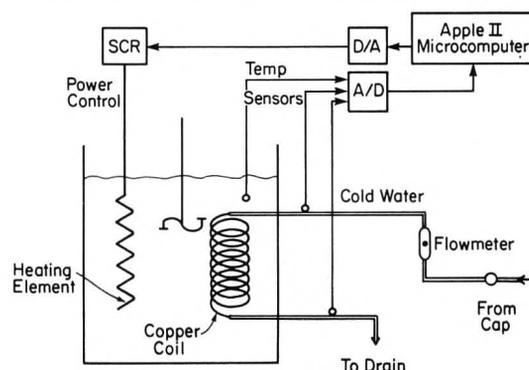


FIGURE 2. Temperature control experiment.

TABLE 1  
List of Experiments

FIG.	EQUIPMENT USED	EXPERIMENTS*
2	Stirred Pot	<ul style="list-style-type: none"> <li>• Calibration of a Temperature Sensor</li> <li>• Modeling the Dynamics of the Heated Tank</li> <li>• Feedback Control of Temperature</li> </ul>
3	Pressurized Tank	<ul style="list-style-type: none"> <li>• Calibration of Pressure Sensor</li> <li>• Dynamics of Tank Pressure</li> <li>• On-off Control of Pressure</li> </ul>
4	Hot and Cold Water Mixing Tank	<ul style="list-style-type: none"> <li>• Calibration of Level Sensor</li> <li>• Dynamics of Tank Level</li> <li>• Feedback Control of Tank Level</li> <li>• Multivariable Control of Level and Temperature</li> </ul>
5	Heated Bar	<ul style="list-style-type: none"> <li>• Data-logging Using a Multiplexer</li> <li>• Steady state Modeling</li> <li>• Feedback Control of Temperature</li> <li>• Cascade Control</li> </ul>
6	pH Control	<ul style="list-style-type: none"> <li>• Titration Curve Measurement</li> <li>• Feedback Control of pH</li> <li>• Nonlinear feedback Control of pH</li> </ul>

\*A detailed manual describing the hardware used and detailing the experiments is available from the authors.

version. These are limited to 8-bits of accuracy. For the experiments described here, this was sufficient. It is estimated that a basic system consisting of the Apple computer, one disk drive, a monitor, a clock and a AD/D-A board can be purchased for less than \$3000 at current market prices. This, in fact, is the major cost of setting up the laboratory. The experiments themselves are homebuilt. Fig. 1 shows the sketch of a typical computer system configuration.

#### EXPERIMENTAL SETUPS

The laboratory consists of five experimental setups, all built by undergraduate students as part of independent study projects. Figs. 2-6 show the schematic of each experimental setup and Table 1 lists the experiments performed with these setups.

The stirred-pot experiment shown in Fig. 2 is perhaps the easiest one to build and work with. The experiment centers around measurement and control of the temperature of water in a stirred coffee pot. The power input in the heating element can be manipulated by the computer. The students get a chance to develop some simple dynamic models and verify the theory by comparison with experimental data. Also this setup allows the study of different types of feedback control laws such as proportional only, PI, and PID.

The pressurized tank setup, shown in Fig. 3, offers an opportunity to study the behavior of surge vessels. The dynamics are easy to model and verify experimentally. The solenoid valves allow

on-off control of tank pressure. The needle valves allow the time constants to be adjusted. This experimental setup is adapted from a similar experiment at the University of California, Santa Barbara.

Fig. 4 shows the schematic of an experiment to study multivariable control. This setup is discussed extensively in the recent book by W. H. Ray on advanced process control. The setup is used initially to study control of level alone and then to study the simultaneous control of level and temperature.

Fig. 5 shows the schematic of the heated-bar setup, another experiment that was adapted from the University of California at Santa Barbara. This setup introduces the concepts of multiplexing (using one channel to collect multiple data); it also enables the study of cascade control systems where the temperature at one end of the bar is controlled by adjusting the set point of an inner temperature control loop.

The pH control setup shown in Fig. 6 was built to demonstrate the effect of nonlinearities in feedback control. A simple nonlinear feedback controller can be designed to achieve good pH control in this case.

Additional equipment in the laboratory include a small analog computer which allows one to do hybrid computing. For example a simple third order process can be simulated on the analog controller and then hooked up with the digital computer for feedback control study.

### COURSE OUTLINE

This course is taken mainly by seniors in chemical engineering and SSM (systems science and mathematics). It is assumed that the students have been exposed to a course in control so that they are familiar with basic concepts of feedback control, block diagrams representation, and transfer functions. The course, which consists of one hour lecture and three hours of laboratory, covers the topics shown in Table 2. Note that we give the students some exposure to advanced control such as feedforward, cascade, and multivariable control. During the last few weeks of the course, lecture time is devoted to cover topics of special interest to the students. Students are required to complete a project which may involve the design of new experiments with the existing equipment or by building new setups. This gives them an opportunity to explore any one aspect of the subject area in a little more depth. □

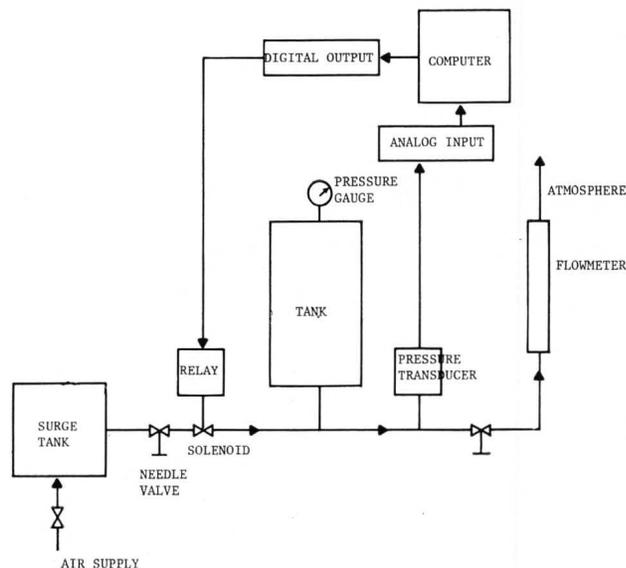


FIGURE 3. Pressure control.

TABLE 2  
Course Outline

WEEK	LECTURE	LABORATORY
1	Programming in Basic, Programming the Apple Computer	
2	Introduction to Real-Time Programming	Experiments using the Real-time Clock
3	Basics of Signal Processing A/D-D/A Conversion Fundamentals	Calibration of Temperature Sensor
4	Modeling of Dynamic Systems	Dynamics of the Temperature Sensor
5	Feedback Control of Processes	Modeling and Control Experiments based on each of the Setups in the Lab.
6	Analysis of Feedback Control Systems	" "
7	Feedforward Control	" "
8	Cascade Control	" "
9	Multivariable Control	" "
10	Current Methodology of Computer Control	Implementation and Testing of Advanced Control Methods
11-14	Advanced Topics of Special Interest such as Fast Fourier Transform, Digital Filtering, Identification, Multi-tasking, Computer Architecture, etc.	Project

## ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to the National Science Foundation, the Apple Foundation and the School of Engineer-

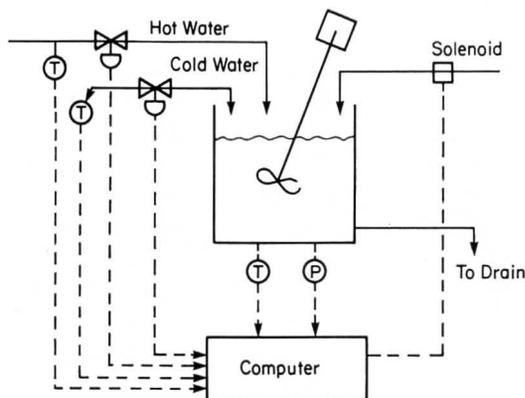


FIGURE 4. Temperature and level control.

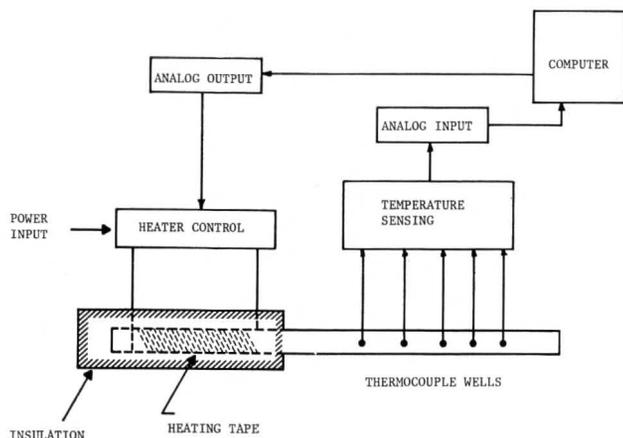


FIGURE 5. Heated bar experiment.

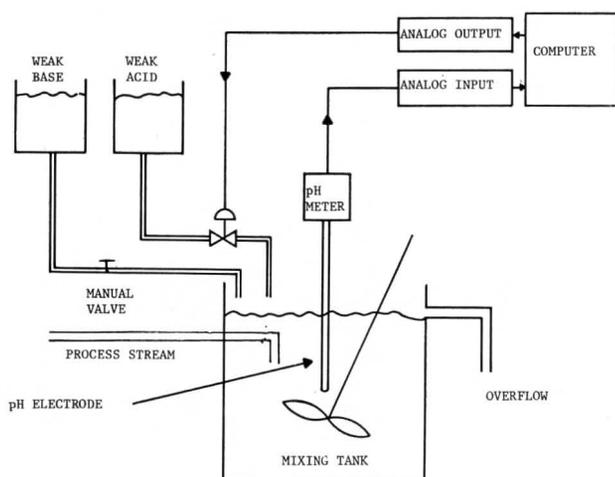


FIGURE 6. pH control experiment.

ing at Washington University for providing financial support for the laboratory through equipment grants. Special thanks to our student, Dale Millard, who worked diligently on the hardware for the experiments and invented the power-controller circuit.

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## ChE book reviews

### CHEMICAL AND PROCESS THERMODYNAMICS

by B. G. Kyle

Prentice-Hall, Inc., 1984, xvi + 512 pgs. \$37.95

Reviewed by Truman S. Storvick  
University of Missouri-Columbia

It appears that all chemical engineering thermodynamics textbooks are created equal. Each author intends to provide the student with an introduction to the subject and to show how specific applications in process design calculations can only be done by careful applications of the principles of equilibrium thermodynamics. Because this subject is the foundation of all chemical engineering, there have been many books written on the subject.

Professor Kyle has done what all authors have done with this subject the past two decades. He has taken the basic ingredient list assembled by Dodge [1] and by Hougen and Watson [2] and brought it up to date with new experimental data and worked examples. The ordering of the topics is not the same as one finds in the textbooks written by Smith and Van Ness [3] or by Sandler

Continued on page 145.

## KINETICS AND CATALYSIS DEMONSTRATIONS

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CLASSROOM DEMONSTRATIONS ARE valuable additions to a lecture course in kinetics and catalysis. Over the last few years we have used a number of short demonstrations in class to show that catalysts can dramatically increase the rates of chemical reactions. These demonstrations are also used to show the different types of catalysts and their properties and the effects of temperature, concentration, and heat transfer on reaction rates. We have found, however, that videotapes of these demonstrations have many advantages over live demonstrations:

- Noise, odor and safety are all controlled for a videotaped demonstration
- Chemicals and solutions, which can degrade in a year, do not have to be reordered or remade each year
- Time is not spent setting up gas cylinders, beakers, hot plates, liquid nitrogen dewars, safety shields and so forth in a classroom. Setup of a VCR machine and a TV screen takes very little time
- Smaller and safer quantities of chemicals can be used. A 50 ml beaker will fill the entire TV screen when a zoom lens is used, and a white background makes color changes easily visible. Thus, a better demonstration results by videotaping a reaction in a 50 ml beaker than for a live demonstration with a 500 ml beaker
- An elevated 21-inch TV screen can be easily seen by all students in the class
- Videotaped demonstrations are guaranteed to work on the first try

Short descriptions of each of the demonstrations that we have videotaped and shown

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**A more dramatic demonstration of hydrogen oxidation results when the oxygen concentration is increased by using pure oxygen instead of air. . . . The mixture reacts explosively, and very loudly.**

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during the semester are presented. Because we cover a range of topics in the lectures, demonstrations are shown for acid and zeolite catalysis, solution catalysis, and supported and unsupported metal catalysis. In general, these are not new demonstrations; they have been described previously and are compiled here for easy use. The resulting videotapes are not professional quality, but they demonstrate the important points very effectively. *Note that many of these reactions are dangerous and must be done carefully in a hood and with safety glasses.*

### 1. CLOCK REACTION

This is the standard kinetics demonstration that can be used to show the effects of temperature, concentration and a catalyst on the rate of reaction [1, 2]. Fifty ml of solution A and 50 ml of solution B are combined in a 250 ml beaker. Then, 50 ml of solution C are added, and the mixture is stirred until reaction is complete, as indicated by a color change from cloudy to blue. For the solution concentrations listed below, at room temperature the blue starch complex forms after 25 s.

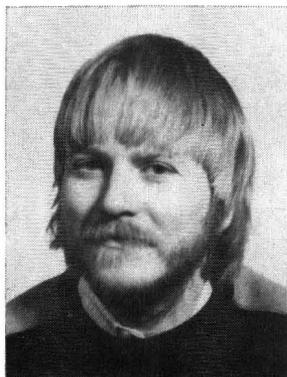
Since the reactions are not first order, reaction time is increased significantly by addition of distilled water to the mixture. Similarly, reaction time is decreased by heating above room temperature. By adding a small amount of  $\text{FeSO}_4$  solid, which acts as a catalyst [2], reaction time is decreased to 10 s.

#### Solutions

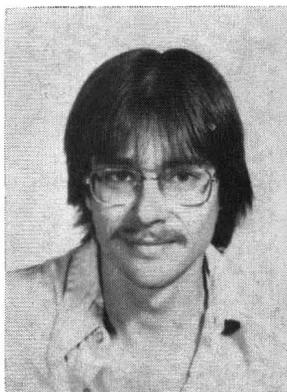
- A: 5.5 g  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  dissolved in distilled water to yield one liter of solution;  
 B: 0.13 g  $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$  dissolved in distilled water to yield one liter of solution;  
 C: 50 ml KI dissolved in 600 ml of 10% potato starch solution, which is then diluted with distilled water to one liter.

### 2. OSCILLATING REACTION

This demonstration, which has been called the color blind traffic light [3, 4], shows the unusual



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**Jerald A. Britten** is a PhD student in the Department of Chemical Engineering at the University of Colorado. He completed his BS at Michigan State in 1979 and his MS at Colorado in 1981. His PhD thesis work involves modeling of instabilities in combustion in porous media. (R)

behavior that can occur in a complex reaction system. It is easy to prepare and is described in detail by Lefelholz [3] and Boulanger [4]. It can also be used to show the effects of temperature and concentration on reaction rates.

The following solution is prepared in 3 N  $\text{H}_2\text{SO}_4$ :

0.005 M ceric ammonium sulfate

$(\text{Ce}(\text{NH}_4)_4(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O})$  ;

0.1 M malonic acid ( $\text{C}_3\text{H}_4\text{O}_4$ ) ;

0.05 M potassium bromate ( $\text{KBrO}_3$ ).

This solution is heated with agitation to  $40^\circ\text{C}$  and about 40 drops of the redox indicator ferroin (1,10-phenanthroline ferrous sulfate complex) are added dropwise. The solution immediately begins to change color from violet to blue and back to violet, with a period of about 50 s, as the concentrations of  $\text{Ce}^{3+}$  and  $\text{Ce}^{4+}$  oscillate periodically. The ferroin changes color as the oxidation state of Ce ion changes. The color change is clearly recorded by the camera against a white background. The period of oscillation depends on the degree of agitation provided by a magnetic stirrer, and is lengthened to 72 s upon addition of about 2 ml of indicator added at once. The solution concentrations are not critical but a single portion of ferroin added at once can create a long induction period [4].

### 3. HYDROGEN OXIDATION IN AIR

Oxidation of hydrogen in air over supported metal catalysts is used to show activity differences

of metals and the increase in rates that occurs with increased surface area. This demonstration also shows how heat removal can be limiting for exothermic reactions on supported catalysts.

A half-inch diameter, vertical brass tube is used to support a wire mesh screen on which a piece of tissue paper is placed. A catalyst sample is placed on top of the tissue, and hydrogen from a gas cylinder is flowed into the bottom of the tube through a tygon tube. For 0.3 g of a 5% nickel/silica catalyst, nothing is observed. Similarly for 0.3 g of pure platinum wire, no visible indications of reaction are seen. However, when a 0.3 g sample of a 5% platinum/silica catalyst is placed on the tissue, significant reaction occurs. The heat released by the reaction heats the catalyst until it glows red, and after less than a minute the tissue paper ignites. Small quantities of catalyst and thus low flow rates of hydrogen can be used, since the camera zoom lens is used to fill the screen with the catalyst and make this demonstration visible.

### 4. HYDROGEN-OXYGEN EXPLOSION

A more dramatic demonstration of hydrogen oxidation results when the oxygen concentration is increased by using pure oxygen instead of air [5]. A 6-oz taped bottle is filled with approximately a 2:1 mixture of  $\text{H}_2$  and  $\text{O}_2$  and then sealed with a rubber stopper. The exact ratio is not critical. The stopper is then removed and approximately 0.1 g of powdered, supported platinum catalyst is dropped into the bottle from a spatula. The mixture reacts explosively, and very loudly. When a piece of white paper is taped to the back of the bottle and low background light is used, a flame is seen shooting out the top of the bottle. This demonstration shows that catalysts can dramatically increase reaction rates; the reaction is extremely slow at room temperature in the absence of a catalyst. It can also be used to show the effect of surface area since a platinum wire dropped in the bottle does not cause an explosive reaction.

Larger bottles (10 oz and 15 oz) have been used for this demonstration, but they are not safe for a classroom demonstration because the noise is almost deafening. This demonstration should be done with great care; the platinum catalyst must be completely cleaned out of the bottle before a repeat experiment is attempted.

### 5. ACID-BASE PROPERTIES OF SOLIDS

The fact that many solid oxides which are used as catalysts or catalyst supports have acidic sites

and basic sites is easily shown using indicators for powders suspended in solution. No quantitative measure of acid strength is made, but the presence of acidic and basic sites and the differences between oxides are easily shown.

A series of 250 ml beakers are each filled with 50 ml of distilled water which contains a small amount of dissolved bromothymol blue indicator. This indicator changes from yellow to blue over a pH range from 6.0 to 7.6. In our case it was yellow in distilled water. Ten to fifteen grams of a powdered oxide ( $\gamma$ -zeolite,  $\text{SiO}_2 \cdot \text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$  and  $\text{SiO}_2$ ) are added to each beaker. Malonic acid and sodium hydroxide are also added to two beakers to show the similarity between liquid acids and bases and solid acids and bases.

The malonic acid produces no color change. The zeolite powder produces a dirty-yellow, cloudy appearance in the solution, which turns light green over a period of minutes. The silica-alumina powder does not change the color of the solution significantly. The titanium dioxide powder forms a milky suspension with the water, with a slight blue-green tinge. Alumina powder changes the solution to a deep blue-green color. Magnesia powder produces a deep blue when added. The  $\text{NaOH}$  solution turns the indicator solution a very dark blue. Two samples of powdered  $\text{SiO}_2$  were used. One caused no appreciable color change of the solution, indicating acidity, while the other sample turned the solution a dirty blue-green of intensity less than that of the  $\text{Al}_2\text{O}_3$  mixture. Differing treatment histories of these silica samples are probably the cause of this discrepancy.

The acid-base properties of most of these solids are strongly dependent on such factors as temperature, duration of heat treatment, and the amount of adsorbed water. The order of acid strength given for these solids will be different if a non-polar solvent is used instead of water [6]. Water interacts significantly with solid surfaces and can alter the acidic character. Impurities in the solids can also affect acidity. For example, aluminas are usually weakly acidic, but this can be enhanced significantly by impurities such as a chloride. Some commercial aluminas are basic, in that a suspension in water exhibits a pH above 7, which is caused by the presence of sodium.

## 6. HIGH-TEMPERATURE ZEOLITE REACTIVITY

A rare-earth exchanged x-zeolite can be used to show the properties of solid acids for hydrocarbon cracking [7]. Three and one-half grams of

paraffin wax are placed in each of two 50 ml beakers and heated with a hot plate to  $260^\circ\text{C}$ . At this temperature, the wax is a liquid. Into one beaker is dropped one gram of the zeolite powder, and into the other beaker  $\text{SiO}_2$  or  $\text{SiO}_2 \cdot \text{Al}_2\text{O}_3$  powder is added. A slight bubbling is seen for silica or  $\text{SiO}_2 \cdot \text{Al}_2\text{O}_3$ , but vigorous reaction occurs almost immediately for the paraffin in contact with the zeolite. When both beakers are cooled after a few minutes of reaction, the paraffin in the zeolite-containing beaker has turned dark, while the paraffin in the other beaker has not. This demonstration is particularly convenient on videotape since it is not necessary to wait in class for the cooling to occur. Also, a rather unpleasant odor is given off by the hot wax, and 50 ml beakers minimize this. These small beakers would be difficult to see in a live demonstration, however.

## 7. LOW-TEMPERATURE ZEOLITE REACTIVITY

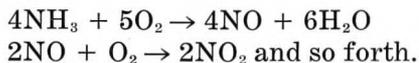
The ability of catalysts to accelerate reactions even at very low temperatures is shown by isoprene cracking below  $-146^\circ\text{C}$  [7].

Approximately 5 ml of isoprene (2-methyl-1,3-butadiene, m.p.  $-146^\circ\text{C}$ ) in a test tube are frozen by immersion in liquid  $\text{N}_2$  for about one minute. The test tube is mounted on a stand in front of a white background for good contrast, and a gram of baked zeolite powder is poured into the tube on top of the solid isoprene. As the isoprene melts and contacts the zeolite, it immediately cracks and turns a light brown color. When a powdered silica-alumina catalyst is used, the isoprene remains colorless. The color change of the zeolite-contacted isoprene is pronounced enough to be easily recorded by the camera, providing that ice, which deposits on the side of the tube after removal from the  $\text{LN}_2$  bath, is periodically wiped off. A more pronounced color change, with the formation of a black solid, occurs when two grams of baked zeolite are added to 5 ml of isoprene. Also, some spattering of the zeolite occurs. With more zeolite, a violent reaction occurs and the entire mass turns black [7].

## 8. COPPER CATALYSIS OF $\text{NH}_3$ OXIDATION AND SODIUM PEROXIDE DECOMPOSITION

This demonstration, described by Koch [8], shows both gas-phase and liquid-phase catalysis. Copper metal is used to catalyze the oxidation of ammonia, and cupric ion catalyzes the decomposition of sodium peroxide. Ammonia is obtained from 60 ml of concentrated ammonium hydroxide

in a 250 ml flask. Four grams of sodium peroxide are slowly added and some decomposition takes place. A cone of copper (made from a circle of copper foil) of approximately one inch diameter is heated to a red glow and suspended in the flask about two inches above the liquid surface. The cone is suspended from a wire through a hole in the top of the cone. The hot copper catalyzes the oxidation of gas-phase ammonia to NO and H<sub>2</sub>O [8]:



The cone continues to glow as heat is generated by the oxidation reaction.

The generation of oxygen can also be catalyzed by the addition of 1 M copper sulfate, since cupric ion catalyzes the decomposition of sodium peroxide:



A drop of the copper sulfate solution will increase the rate of oxygen production significantly. An almost detonating mixture can be formed [8].

## 9. AMMONIA OXIDATION AND REACTOR STABILITY

An experiment that is similar to the previous one can be used to demonstrate both catalytic activity and reactor stability. Hudgins [9] described this experiment in detail, and it will be only briefly summarized here. Concentrated ammonium hydroxide solution is placed in the bottom of a 200 ml erlenmeyer flask, and a copper wire is heated to incandescence and suspended above the solution. Copper wires of different diameters (No. 12, 18, 24), were used; the smallest wire melts, and the glow of the largest wire very slowly diminishes. The No. 18 wire, however, continues to glow for some time. Hudgins [9] indicated these results for different size wires demonstrate control of a catalytic reaction by heat transfer across a film. However, it appears that the heat and mass transfer coefficients increase as the wire diameter decreases for a horizontal wire [10]. Thus, this reaction may be controlled by mass transfer.

To demonstrate reactor stability, the wire is withdrawn from the flask and then quickly replaced when the glow fades; the wire starts glowing again. A larger perturbation in temperature extinguishes the glow. This demonstration can also be used to show that transient temperatures are easily produced in catalyst particles with exothermic reactions [9]. The glowing wire shows up extremely well on videotape.

## 10. OXIDATION OF TARTARIC ACID

This is an excellent example of solution catalysis, the role of a complex as an intermediate, and the effect of temperature on reaction rate [11]. Color changes, which indicate the presence of an intermediate, are marked and show up well on the videotape when filmed against a white background.

A 0.3 M aqueous solution of potassium sodium tartrate (KNaC<sub>4</sub>H<sub>6</sub>O<sub>6</sub>·4H<sub>2</sub>O) is prepared, and 300 ml are mixed with 100 ml of 6% H<sub>2</sub>O<sub>2</sub> in a 700 ml beaker on a stirred hot plate. The tartrate solution is heated to 50°C with magnetic stirring, and 25 ml of a 0.3 M aqueous CoCl<sub>2</sub> solution is added. Immediately after addition of the cobalt, the solution is light pink. After a few-second induction period the solution changes to a dark green as a cobalt-tartrate complex is formed as an intermediate. The oxidation of tartrate is evidenced by the vigorous evolution of CO<sub>2</sub> gas. This frothing necessitates use of the large beaker. As the reaction goes to completion and gas production stops, the solution returns to its original light pink hue as the original cobalt is reformed. The total time of the reaction, as measured by this color change, is 133 s. At 60°C the induction time is markedly shorter, the reaction more vigorous, and the reaction time measured by the color change is 63 s. No reaction is observed before addition of the cobalt solution at either temperature.

## 11. CATALYST PREPARATION

The various steps in preparation of a supported nickel catalyst by impregnation were videotaped over several days, so that the preparation steps can be condensed into a few minutes of tape. This videotape shows how promoters and nickel salts are added from solution by incipient wetness, and it shows the rapid uptake of water by a porous solid. Samples of the support after various stages in the preparation are also shown in class.

## 12. ADDITIONAL DEMONSTRATIONS

Other demonstrations that may be useful include Raney nickel oxidation, to demonstrate the high reactivity of a high surface area metal, and silica gel preparation from solution.

We usually include a laboratory tour to show the equipment used for catalysis research in chemical engineering. We plan to videotape the operation of this equipment so that the class will have a better idea of its purpose and use. At present, this lab tour includes an Auger spectro-

meter, an XPS spectrometer, a static chemisorption apparatus, differential reactors with gas chromatography, a mercury porosimeter, and a temperature-programmed desorption system.

Since we also discuss bulk and surface structures and Miller indices notation, cork ball models have been used for these structures. Close-up videotapes of the various structures and of zeolite structures will allow students to study them at their leisure. The bulk structures that demonstrate Miller indices notation were prepared using templates for the different symmetries [12].

### SUMMARY

Eleven kinetics and catalysis demonstrations have been briefly described. By videotaping these demonstrations, we are able to easily use them each year in a catalysis and kinetics course. Videotaping improves the demonstrations, makes them more visible and safer, and results in better use of class time. □

### ACKNOWLEDGMENTS

We would like to thank John Ma for his help on some of these demonstrations and Professor David E. Clough for obtaining the videotaping system and encouraging us to use it.

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## REVIEW: Fluidized-Bed Processes

Continued from page 109.

The book is intended mainly for use by final-year undergraduate students or graduate students in chemical engineering. In view of its contents, however, the book should be regarded more as a reference monograph than as a classroom text. The book will also be a useful reference for researchers, development engineers, and designers in the field of fluidization technology. In fact, the book can be recommended to anyone who wishes to be initiated into the science and art of fluidized-bed chemical processes.

The book is indeed concise, containing only 222 pages. Obviously it is extremely difficult, if not impossible, to cover all aspects of fluidized-bed chemical processes in detail in a book of this size. Unfortunately, some topics of current importance are omitted. Examples are the stochastic behavior of fluidized-bed chemical processes and the performance of relatively shallow and wide fluidized bed (or the so-called horizontal fluidized bed). According to Bukur, Carem and Amundson (Chapter 11 of *Chemical Reactor Theory: A Review*, Edited by Lapidus and Amundson, Prentice-Hall, Inc., Inglewood Cliffs, NJ, 1977), "It is our view that probably no deterministic model will ever describe such reactors with any precision." The horizontal flow fluidized beds have been used extensively to process solid materials because these fluidized beds tend to yield better quality and higher conversion of solid products than conventional vertical fluidized beds. □

### PROBABILISTIC ENGINEERING DESIGN: PRINCIPLES AND APPLICATIONS

by James N. Siddall

Marcel Dekker, Inc., 1983; 544 pages, \$65.00

Reviewed by Ernest J. Henley  
University of Houston

Probabilistic design and risk analysis have been my 'bread and butter' research activities for the past fourteen years. It's been a lonely road: most chemical engineering academicians appear to have convinced themselves, and each other, that the path to the podium lies in double-precision, deterministic models (based, frequently, on experimental evidence as reliable as the Las Vegas gaming tables). At our shop, the required BS course in statistics has gone the way of under-

graduate literacy and the PhD language requirement. Indeed, I have become so inured to this bias that I was genuinely delighted to receive Professor Siddall's book, "Probabilistic Engineering Design," for review from the editors of this esteemed journal. At long last; somebody cares!

Before editorializing further, let me describe what is in this book and its strong and weak points. Chapters 2-5, in the author's words, "provide a review of the necessary material and background for the text." These 145 pages describe the concepts and theorems of probability, probability distributions, moments of a distribution and generation of probability density functions. The level of scholarship is high, the presentation is excellent and the examples are interesting, current, and pertinent. Although I find myself occasionally disagreeing with Professor Siddall, I admire his courage in telling it like he sees it. For example, only in the Appendix do we find a (brief) discussion of confidence limits for distributions because, the author tells us, engineering intuition is a better basic tool in risk decision making.

The rest of the chapters cover: (6) Probabilistic Analysis (Primarily Monte Carlo and moment relationships); (7) Sequential Events (Markov chains, Monte Carlo, Random Time Functions); (8) Order Statistics and Extreme Values; (9, 11, 12) Reliability and Failure Modes; (10) Design Options (only 14 pages); (13) Optimization (four pages only).

From page 145 on, the treatment and topics become somewhat uneven. Professor Siddall, at times, loses patience with his readers. Advanced Monte Carlo methods are developed in detail; basics are almost ignored. The author assumes that the reader is sufficiently familiar with Lagrangian multipliers and Newton-Raphson techniques that he uses them without explanation (or listing them in the index). Markov chains are accorded one paragraph: we are told that problems that can be solved by Markov methods are better solved by Monte Carlo. One of Professor Siddall's research interests, E. T. Jaynes' maximum entropy principle, is accorded quite a bit of space in this text. Personally, I feel the same way about the maximum entropy principle as the author feels about Markov methods, but why should we agree on everything?

A very nice feature of this book is the copious computer programs which appear throughout. Also, a well documented, 105-page software package for probabilistic design forms one of the Ap-

pendices.

This is an excellent, well-written, interesting book. I enjoyed it, and I am unabashedly pleased to have been cited four times in the Author Index. The crying shame of it all is:

- a) The publisher printed it on cheap paper from typed, hard-to-read copy. The equations occupy too much space, and the price (\$65.00) is outrageous.
- b) Every chemical engineering curriculum should have a required course based on the material in this book: none do. Of course, there is no room for this, and many other things, in our aborted four-year curriculum. If we went to a five- or six-year curriculum there would be; and, if we did this, then maybe the Copley Square Hotel in Boston would not have the Chutzpah to give its head janitor the title of "Engineering Consultant." □

## REVIEW: Process Thermodynamics

Continued from page 139.

[4], for example. Ordering the presentation may be more a matter of style than pedagogical necessity.

The first eight chapters, or about one third of the book, cover the first law, second law,  $pVT$  behavior, thermal effects and the calculation of the thermodynamic properties of matter. The classical Carnot engine—Clausius inequality development of the entropy function is used in this treatment. Phase equilibrium and chemical equilibrium each occupy about 100 pages of material. The last 100 pages are given to thermodynamic analysis of processes, physico-mechanical processes and compressible fluid flow. The text is carefully crafted and free of troublesome production errors. There are numerous worked examples and the list of exercises for students seems adequate.

"One may reasonably ask, 'Why another book on thermodynamics; are there not more than enough on this subject now?'" is the opening sentence in the preface to B. E. Dodge's book. Forty years and many textbooks later Professor Kyle has written another traditional chemical engineering thermodynamics textbook. We all agree on the major topics and tradition may have bound us to small variations in development and presentation. If you are using one of the widely adopted textbooks in your course this book could serve you. The best textbook for me and for you is the one our students can read and that matches

our teaching style. Professor Kyle has given us yet another option in that tradition. □

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## LOST-WORK STATEMENTS

Continued from page 131.

reversible path that brought the system from State 1 to State 2. But if that path produced useful work, we could have stored it and used it to partly offset the work of restoration; if it produced no useful work, then all of the work of restoration must be supplied externally. Hence the thermodynamic lost work, as apparently first stated by Van Ness [14] is the work to restore the system minus the external work produced.

We can now proceed to complete Table 1, which shows the differences in properties of the two definitions of lost work. The first question is whether they are unambiguously defined for non-isothermal systems. From the definitions in terms of  $dS_{irr}$ , it is easy to see that  $LW_t$  is unambiguously defined for a non-isothermal system because the system temperature does not appear in its definition (only the infinite surroundings temperature does). The system temperature is implicitly present in the  $dS_{irr}$  term, but that is unambiguous. On the other hand,  $LW_m$  has a  $T$  in its definition in terms of  $dS_{irr}$ . If that  $T$  is constant, both in space and in time, then the definition is unambiguous. But if it is not, then there is no unambiguous definition of  $LW_m$ . For example, we could consider the irreversible flow of heat through a solid conductor from a reservoir at  $T_h$  to one at  $T_c$ . Here

$$dS_{irr} = dS = dQ \left( \frac{1}{T_c} - \frac{1}{T_h} \right) \quad (14)$$

so

$$dLW_t = T_o dS_{irr} = dQ \left( \frac{T_o}{T_c} - \frac{T_o}{T_h} \right) \quad (15)$$

and

$$dLW_m = T dS_{irr} = dQ \left( \frac{T}{T_c} - \frac{T}{T_h} \right) \quad (16)$$

$LW_t$  is perfectly unambiguous, but  $LW_m$  is only defined if we can define a proper value for  $T$ . We could set it equal to  $T_c$ , in which case  $LW_m$  is equal to the work that would have been produced by a Carnot engine withdrawing  $dQ$  of heat from the high-temperature reservoir and operating between  $T_h$  and  $T_c$ . Or we could set it equal to  $T_h$ , in which case  $LW_m$  would be equal to the amount of work that a Carnot engine would produce by withdrawing  $(T_h/T_c)dQ$  of heat from the high-temperature reservoir and rejecting  $dQ$  of heat to the low-temperature reservoir. One could persuasively argue for either of these values or perhaps for some intermediate one. The point is that there is no obvious or unambiguous definition of  $LW_m$  for this case. Van Wylen and Sliepcevich have tried to deal with this problem. Van Wylen [16] says

In summary, the lost-work concept assumes that there is a reservoir available at the temperature  $T$  required for the given situation. The concept of irreversibility assumes heat transfer with the surroundings only at temperature  $T_o$ .

Here he is clearly referring only to  $LW_m$  and does not mention the existence of the other definition ( $LW_t$ ). Van Wylen uses another quantity which he calls "irreversibility" which is identical to what we call  $LW_t$ .

Sliepcevich [11] says

It is apparent that the evaluation of the terms  $\delta(Q_i/T_i)$  and  $(\delta l_w/T)$  in Eq. (4-155) [a general entropy balance] will pose certain difficulties either if the temperature of the system is not uniform throughout or if the temperature, even though uniform throughout, changes during the process.

and also

Note that the latter [Eq. 4-193, a steady flow entropy balance using  $LW_m$ ] cannot be solved explicitly for  $(dQ)_i$  or  $(dLW)_i$  unless the temperature of the system  $T$  is constant and uniform throughout, in which case,  $T_i = T = T_i = T_o$ . For this very special case, Eq. 4-193 yields....

These three statements must surely have convinced any practitioner that the lost work definition to which they apply, ( $LW_m$ ), is of very little, if any, practical utility.

The next line on Table 1 asks whether the two values of  $LW$  are computable without reference to the surroundings temperature.  $LW_m$  obviously is because in its definition, nothing related to  $T_o$  appears. One unit of mechanical work converted to internal energy has the same value of  $LW_m$  whether it is at the temperature of the sun or that of liquid helium. On the other hand,  $LW_t$  cannot be

computed independently of the surroundings temperature. If the surroundings temperature is, for example, 20°C, then the conversion to frictional heat of one unit of mechanical work has a value of  $LW_t$  less than one unit for system temperatures greater than 20°C and more than one unit for system temperatures lower than 20°C.

To close this section, consider a non-thermodynamic analogy that may clarify the distinction between the two kinds of lost work. If one drops a bottle of wine on his kitchen floor and the bottle breaks, then he has certainly lost the wine. The  $LW_m$  is analogous to the assertion that what is lost is the wine. The  $LW_t$  is analogous to the assertion that not only is the wine lost, but also someone must clean the kitchen floor.

### REVERSIBLE WORK OR COMBINED-LAW STATEMENTS

To consider the next line in Table 1, we must introduce the idea of the reversible work, or the combined first- and second-law statement. We believe that the simplest way to show such a statement is to begin with open-system, unsteady-state energy and entropy balances,

$$d(mu)_{\text{sys}} = \sum_j h_j dm_j + \sum dQ_i - dW \quad (17)$$

$$d(ms)_{\text{sys}} = \sum_j s_j dm_j + \sum_i \frac{dQ_i}{T_i} + \frac{dLW_t}{T_o} \quad (18)$$

Then we multiply Eq. (18) by  $T_o$  and subtract it from Eq. (17), finding (after rearrangement)

$$dW + dLW_t = \sum_j (h - T_o s)_j dm_j + \sum_i \left(1 - \frac{T_o}{T_i}\right) dQ_i - d[m(u - T_o s)]_{\text{sys}} \quad (19)$$

or, in terms of the availability function ( $b = h - T_o s$ ),

$$dW + dLW_t = \sum_j b_j dm_j + \sum_i \left(1 - \frac{T_o}{T_i}\right) dQ_i - d[m(b - Pv)]_{\text{sys}} \quad (20)$$

The sum of the two terms on the left of the equal sign is the reversible work

$$dW_{\text{rev}} = dW + dLW_t \quad (21)$$

for a process occurring in the system and having the same initial and final states of the system, the same flows of matter in and out, and the same exchanges of heat at all temperatures except  $T_o$ .

This equation has the remarkable property of showing that the sum of two path functions ( $dW$  and  $dLW_t$ ) form a state function.

Here we use the term "state function" in a

somewhat broader sense than it appears in many thermodynamics texts. There it refers to a property of a fixed mass of matter, like entropy, showing that the changes of this property depend only on the initial and final states of the system, and do not depend on the path taken to get from the initial to the final state. Here we expand that idea to include the possibility that there is heat exchange with the system at temperatures other than  $T_o$  and that there may be flows of matter across the system boundaries.

The value of  $dW_{\text{rev}}$  can be computed unambiguously for any system using only the terms on the righthand side of Eq. (19) or (20); i.e., the data on the initial and final states of the system and the flows of heat and matter across its boundaries. (It is not necessary to know the value of  $dQ$  at  $T_o$  or of  $dW$ .) If we also have data on  $dW$  or on  $dQ$  at  $T_o$ , it allows an equally unambiguous computation of  $dLW_t$ .

Is the same type of formulation possible for  $LW_m$ ? Apparently not. If we substitute from Eq. (13), we find

$$dW + \frac{T_o}{T_{\text{sys}}} dLW_m = \sum_j b_j dm_j + \sum_i \left(1 - \frac{T_o}{T_i}\right) dQ_i - d[m(b - Pv)]_{\text{sys}} \quad (22)$$

but unless the system is isothermal, both over time and space, there seems no way to evaluate or attach meaning to the lefthand side of Eq. (22). Thus, in Table 1 we indicate that  $LW_t$  leads to an unambiguous combined statement but that  $LW_m$  does not.

It is also interesting to ask who introduced Eq. (20) or its equivalents into engineering. The fundamental ideas go back as far as Gibbs [7]. The idea of maximum reversible work, exchanging heat only with the surroundings at  $T_o$ , goes back at least as far as Gouy [8] and Stodola [13]. Kestin [9] refers to the basic result as the "Gouy-Stodola Theorem."

Brown and Sliepcevich [2] show an equation similar in form to Eq. (20) (using what they called  $(lw)_o$ ), including terms for kinetic and potential energy but without the terms for a change in the system nor for heat flows at temperatures other than  $T_o$ . Martin [10] devotes a considerable fraction of his thermodynamics slides to developing equations of the same form and content as Eq. (20). Denbigh [6] thoroughly works out a batch equivalent of Eq. (20) and indicates how one would find the open-system equivalent. Smith and Van Ness [12] also show forms that are equivalent

to Eq. (20). Certainly others could be cited.

## THE UTILITY OF LOST WORK AND THE COMBINED STATEMENT

As shown elsewhere [4, 5], the lost-work approach to second-law analysis of processes is generally simpler than the competing approaches. Its assumptions and limitations are clearly stated and can be removed when needed (e.g., one easily can include terms for kinetic energy, etc.). The combined statement is one of extreme power and generality, which should occupy a central place in any treatment of thermodynamic efficiency.

## CONCLUSIONS

The adoption and use of the lost-work concept has been strongly hindered by the existence, in the chemical engineering literature, of two very different quantities that both bear the name "lost work."

The "thermodynamic lost work" is much more useful and practical than the "mechanical lost work." Using the thermodynamic lost work, one can formulate a combined statement of the first and second laws, which shows that, although the actual work and the lost work are path functions, their sum, the reversible work, is a state function. This allows the direct computation of the reversible work of irreversible processes. □

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## NOTATION

b	availability function per unit mass ( $h - T_0s$ ), J/kg
h	enthalpy per unit mass, J/kg
lw	lost work (used in Brown and Sliepcevich papers), J
(lw) <sub>T</sub>	lost work of an isothermal process (used in Brown and Sliepcevich papers), J
(lw) <sub>o</sub>	lost work of a process that exchanges heat only with the surroundings at T <sub>o</sub> (used in Brown and Sliepcevich papers), J
LW	lost work, J
LW <sub>m</sub>	mechanical lost work, J
LW <sub>t</sub>	thermodynamic lost work, J
m	mass, kg
P	pressure, pa
Q	heat, J
q	heat (used in Brown and Sliepcevich papers), J
S	entropy, J/°K
s	entropy per unit mass, J/kg°K
S <sub>irr</sub>	irreversible entropy production, J/°K
T	temperature, °K
T <sub>o</sub>	temperature of the infinite surroundings, °K
T <sub>sys</sub>	system temperature, °K
T <sub>c</sub> , T <sub>h</sub>	temperatures of hot and cold reservoirs, °K
v	volume per unit mass, m <sup>3</sup> /kg
V	volume, m <sup>3</sup>
W	work, J
W <sub>rev</sub>	reversible work, J
WCTH	work irreversibly converted to heat or internal energy, J
WTRS	work required to restore a system, exchanging heat only with the infinite surroundings at T <sub>o</sub> , J

## MASS TRANSFER

Continued from page 127.

results which I give for each case. I make the major approximation that the reaction is first order and irreversible, so that things stay simple. For the single crystal, I might begin with a mass balance on the ethane near the crystal

$$0 = D \frac{d^2 c_1}{dz^2} \quad (15)$$

The left hand side is zero because the reaction is assumed to be in steady state, and no reaction term appears because the reaction takes place only at the crystal's surface. After many machinations, I present the result

$$N_1 = \frac{c_{10}}{(1/k_1) + (1/\kappa_2)} \quad (16)$$

where  $N_1$  is reaction rate in moles per crystal area per time and  $c_{10}$  is the bulk concentration. The quantity  $k_1$  describes ethane mass transfer from the bulk to the surface: it is a mass transfer coefficient. The quantity  $\kappa_2$  describes the reaction rate on the catalyst surface. Thus this process involves two steps in series, and is a chemical analog to the resistances in series found throughout transport phenomena.

In contrast, if I describe the same reaction in a porous catalyst, I begin with a mass balance on the ethane in the catalyst:

$$0 = D \frac{d^2 c_1}{dz^2} - \kappa_2' c_1 \quad (17)$$

Again, the value of zero on the left hand side indicates steady state, and the diffusion term accounts for ethane moving into the catalyst pores. Now, however, a reaction term is present, describing the same reaction, now being modeled as if it were homogeneous. The two rate constants are related, but in a non-trivial way

$$\kappa_2' = \frac{a}{(1/k_1) + (1/\kappa_2)} \quad (18)$$

where  $a$  is the surface area per volume of the catalyst, and  $k_1$  now refers to mass transfer from the pores' core to the walls. The solution to Eq. (17) is

$$N_1 = (D\kappa_2')^{1/2} \coth\left(\frac{\kappa_2' d^2}{D}\right) c_{10} \quad (19)$$

where  $d$  is a length characteristic of the pellets' size. This is very different than the result reported in Eq. (16), even though the chemical reaction is identical. No wonder students get confused.

In my teaching, I try to reduce this confusion by first lecturing on heterogeneous reactions and then turning to homogeneous reactions. This split

is artificial, but seems pedagogically effective. In my discussion of heterogeneous reactions, I use examples from non-petrochemical areas like electrochemistry, fermentation, and detergency, since these nontraditional subjects will be more important to our present students than they have been in the past. In the lectures on homogeneous reactions, I cover the more familiar ground of catalyst effectiveness and gas treating with reactive solvents. My presentation is imperfect, but it seems better now than a few years ago.

Splitting the material on heterogeneous and homogeneous reactions does clarify the concept of "diffusion-control." This important area is often carelessly treated in research, even though it is incessantly quoted. It means three separate things. First, for a heterogeneous reaction, "diffusion-control" means that the reaction rate is not influenced by chemical kinetics, although it may be altered by chemical equilibria. The rate for a first order irreversible reaction is found by letting  $\kappa_2$  become large in Eq. (16).

Second, for a homogeneous reaction, "diffusion-control" means that the reaction rate depends on both diffusion and kinetics. For the simple case above, the rate constant as  $\kappa_2'$  becomes large can be found from Eq. (19) to be  $(D\kappa_2')^{1/2}$ . Third, in chemistry, "diffusion-control" refers to a reaction governed by the Brownian motion in a well-mixed solution. Entering graduate students in engineering remember this third definition best.

## CONCLUSIONS

I believe that we can improve our teaching of mass transfer by making three simple changes. First, we need to use a single, simple definition of mass transfer coefficients. Such a definition lets students reinforce their intuition and reduces problem solution by number plugging. Second, we need to alter our use of analogies, which is most easily effected by writing flux equations in more parallel terms. Third, we need to repeatedly stress the differences between the mathematical models used for chemical reactions and the actual chemistry of these reactions.

These three changes have improved my teaching. Still, I use them with a convert's pious zeal, which is infecting. They may not work for you, but I hope that they will galvanize you into continuing efforts to make mass transfer seem easier. After all, the unique parts of our profession deserve our finest efforts. □

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## NOTATION

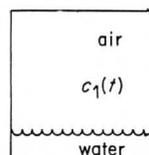
$a$	surface area per volume (Eq. 18)
$c_1$	concentration of species "1"
$C_p$	specific heat capacity
$D$	diffusion coefficient
$f$	friction factor (Eq. 13)
$h$	heat transfer coefficient (Eq. 12)
$j_1$	diffusion flux of species "1"
$k$	mass transfer coefficient
$k', k'', k'''$	alternative mass transfer coefficients (Table 1)
$k$	thermal conductivity
$l$	characteristic "film" thickness (Eq. 1)
$n$	number of moles
$N_1$	interfacial flux of species "1"
$p$	pressure
$p_1$	partial pressure of species "1"
$q$	heat flux
$t$	time
$v$	velocity
$V$	velocity of boundary (Eq. 8)
$V$	volume (Eq. 2)
$x_1$	mole fraction of species "1"
$z$	position
$\alpha$	thermal diffusivity (Eq. 9)
$\kappa_2, \kappa_2'$	reaction rate constants (Eqs. 16-17)
$\mu$	viscosity
$\nu$	kinematic viscosity
$\rho$	density
$\tau$	shear stress

## APPENDIX: THREE SIMPLE EXAMPLES

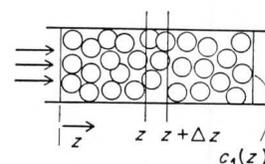
### Example 1: Humidification

Water is evaporating into initially dry air in the closed vessel shown schematically in Fig. 1 (a). The vessel is isothermal at 25°C, so the water's vapor pressure is 23.8 mmHg. This vessel has 0.8 l of water with 150 cm<sup>2</sup> of surface area in a total volume of 19.2 l. After three minutes, the air is 5% saturated. What is the mass transfer coefficient? How long would it take to reach 90% saturation?

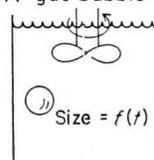
(a) Humidification



(b) Packed bed



(c) A gas bubble



**FIGURE 1. Three easy examples. Each situation leads to a simple problem. In (a) we assume that the air is at constant humidity except near the air-water interface. In (b) we assume that water flowing through the packed bed is well mixed except close to the solid sphere. In (c) we assume that the liquid is at constant composition except near the bubble surface.**

### Solution

The flux at three minutes can be found directly from the values given

$$\begin{aligned}
 N_1 &= \frac{(\text{vapor concentration}) (\text{air volume})}{(\text{liquid area}) (\text{time})} \\
 &= \frac{0.05 \left( \frac{23.8}{760} \right) 1 \text{ mol} \left( \frac{273}{298} \right) 18.4 \text{ l}}{150 \text{ cm}^2 (180 \text{ sec})} \\
 &= 4.4 \cdot 10^{-8} \frac{\text{mol}}{\text{cm}^2 \cdot \text{sec}} \quad (\text{A-1})
 \end{aligned}$$

The concentration difference is that at the liquid's surface minus that in the bulk solution. That at the liquid's surface is the value at saturation; that in the bulk at short times is essentially zero. Thus from Eq. (1) we have

$$\begin{aligned}
 4.4 \cdot 10^{-8} \frac{\text{mol}}{\text{cm}^2 \cdot \text{sec}} &= k \left( \frac{23.8}{760} \frac{1 \text{ mol}}{22.4 \cdot 10^3 \text{ cm}^3} \frac{273}{298} - 0 \right) \\
 k &= 3.4 \cdot 10^{-2} \frac{\text{cm}}{\text{sec}} \quad (\text{A-2})
 \end{aligned}$$

This value is lower than that commonly found for transfer in gases.

The time required for 90% saturation can be found from a mass balance: (accumulation in gas phase) = (evaporation rate)

$$\frac{d}{dt} V c_1 = A N_1 = A k [c_1(\text{sat}) - c_1] \quad (\text{A-3})$$

The air is initially dry, so

$$t = 0 \quad c_1 = 0 \quad (\text{A-4})$$

We use this condition to integrate the mass balance

$$\frac{c_1}{c_1(\text{sat})} = 1 - \exp[-(kA/V)t] \quad (\text{A-5})$$

Rearranging the equation and inserting the values given, we find

$$\begin{aligned} t &= -\frac{V}{kA} \ln \left( 1 - \frac{c_1}{c_1(\text{sat})} \right) \\ &= -\frac{18.4 \cdot 10^3 \text{ cm}^3}{3.4 \cdot 10^{-2} \frac{\text{cm}}{\text{sec}} \cdot 150 \text{ cm}^2} \ln(1 - 0.9) \\ &= 8.3 \cdot 10^3 \text{ sec} = 2.3 \text{ hrs} \end{aligned} \quad (\text{A-6})$$

It takes over two hours to reach 90% saturation.

### Example 2: Mass Transfer in a Packed Bed

Spheres of benzoic acid 0.2 cm in diameter are packed into a bed like that shown schematically in Fig. 1(b). The spheres have 23 cm<sup>2</sup> surface per cm<sup>3</sup> bed. Pure water flowing at a superficial velocity of 5 cm/sec into the bed is 62% saturated with benzoic acid after it has passed through 100 cm of bed. What is the mass transfer coefficient?

#### Solution

The answer to this problem depends on the concentration difference used in the definition of the mass transfer coefficient. In every definition, we choose this difference as the value at the sphere's surface minus that in the solution. However, we can define different mass transfer coefficients by choosing the concentration difference at various positions in the bed. For example, we can choose the concentration difference at the bed's entrance and so obtain

$$\begin{aligned} N_1 &= \frac{0.62 c_1(\text{sat}) (v^0)}{a(lA)} = k(c_1(\text{sat}) - 0) \\ &= \frac{0.62 c_1(\text{sat}) 5 (\text{cm/sec}) A}{23 (\text{cm}^2/\text{cm}^3) (100 \text{ cm}) A} \end{aligned} \quad (\text{A-7})$$

where A is the bed's cross section. Thus

$$k = 1.3 \cdot 10^{-3} \frac{\text{cm}}{\text{sec}} \quad (\text{A-8})$$

This definition for the mass transfer coefficient is infrequently used.

Alternatively, we can choose as our concentration difference that at a position z in the bed, and write a mass balance on a differential volume AΔz at this position: accumulation = (flow in minus out) + (amount of dissolution)

$$0 = A \left[ c_1 v^0 \Big|_z - c_1 v^0 \Big|_{z+\Delta z} \right] + (A\Delta z) a N_1 \quad (\text{A-9})$$

Substituting for N<sub>1</sub> from Eq. (1), dividing by AΔz, and taking the limit as Δz goes to zero, we find

$$\frac{dc_1}{dz} = \frac{ka}{v^0} [c_1(\text{sat}) - c_1] \quad (\text{A-10})$$

This is subject to the initial condition

$$z = 0 \quad c_1 = 0 \quad (\text{A-11})$$

Integrating, we obtain an exponential of the same form as in the first example

$$\frac{c_1}{c_1(\text{sat})} = 1 - \exp[-(ka/v^0)z] \quad (\text{A-12})$$

Rearranging the equation and inserting the values given, we find

$$\begin{aligned} k &= -\left( \frac{v^0}{az} \right) \ln \left( 1 - \frac{c_1}{c_1(\text{sat})} \right) \\ &= -\frac{5 \text{ cm/sec}}{(23 \text{ cm}^2/\text{cm}^3) (100 \text{ cm})} \ln(1 - 0.62) \\ &= 2.1 \cdot 10^{-3} \frac{\text{cm}}{\text{sec}} \end{aligned} \quad (\text{A-13})$$

This value is typical of those found in liquids. This type of mass transfer coefficient definition is the same as a log-mean value.

### Example 3: Mass Transfer from an Oxygen Bubble

A bubble of oxygen originally 0.1 cm in diameter is injected into excess stirred water as shown schematically in Fig. 1(c). After 7 min, the bubble is 0.054 cm in diameter. What is the mass transfer coefficient?

#### Solution

This time, we write a mass balance not on the surrounding solution but on the bubble itself

$$\frac{d}{dt} \left( c_1 \frac{4}{3} \pi r^3 \right) = AN_1 = -4\pi r^2 k (c_1(\text{sat}) - 0) \quad (\text{A-14})$$

where r is the radius of the bubble at any time, t. This equation is tricky: c<sub>1</sub> refers to the oxygen concentration in the bubble, (1 mol/22.4l) at standard conditions; but c<sub>1</sub>(sat) refers to the oxygen concentration at saturation in water, about 1.5·10<sup>-3</sup> mol/l under similar conditions. Thus

$$\frac{dr}{dt} = -k \frac{c_1(\text{sat})}{c_1} = -0.034 k \quad (\text{A-15})$$

This is subject to the condition

$$t = 0 \quad r = 0.05 \text{ cm} \quad (\text{A-16})$$

so integration gives

$$r = 0.05 \text{ cm} - 0.034 \text{ kt} \quad (\text{A-17})$$

Inserting the numerical values given, we find

$$\begin{aligned} 0.027 \text{ cm} &= 0.05 \text{ cm} - 0.034 \text{ k}(420 \text{ sec}) \\ &= 1.6 \cdot 10^{-3} \text{ cm/sec} \end{aligned} \quad (\text{A-18})$$

Remember that this coefficient is defined in terms of the concentration in the liquid, and would be numerically different if it were defined in terms of the gas phase concentration.  $\square$

## DEPARTMENT: Syracuse University

Continued from page 105.

voted to an investigation of transport mechanisms of small molecules in rubbery and glassy polymers, and to some important applications of these mechanisms. The applications include the development of high-selectivity, high-flux membranes for fluid separation processes, the design of controlled drug delivery systems, and the improvement of adhesion of integrated circuits.

**Lawrence L. Tavlarides** is conducting research on chemically reactive turbulent liquid dispersion and chemical reaction kinetics. The objective of the research in liquid dispersions is to provide a fundamental basis for the design and scale up of extractors and reactors. The microscopic droplet rate processes of coalescence and breakup are analyzed with population balance equations and Monte Carlo simulation techniques. Hydrodynamic turbulent flow models are also developed to predict the local turbulent kinetic energy and energy dissipation in mechanically agitated turbulent dispersions. Hydrometallurgical solvent extraction in Tavlarides' group is focussed on multiple metal chelation reactions and chemical equilibria. Intrinsic chemical kinetic models are developed for reactions occurring at or near the liquid-liquid interface using the novel liquid jet recycle reactor. Thermodynamic based heterogeneous equilibrium models are also developed. The above simulation models are employed with the kinetic and equilibrium models to predict conversion and selectivity. Other studies by this group include catalyst deactivation by surface carbon to determine kinetic rate models for synthesis reactions.

**Chi Tien's** major research activities are in three areas: fluid-particle technology, liquid phase adsorption, and biochemical engineering. The fluid-particle technology research covers a broad spectrum of topics including deep bed filtration of liquid suspensions, aerosol filtration in granular

and fibrous media, and in fluidized beds with or without magnetic stabilization, and stratification and segregation of particles in sedimentation and liquid fluidized beds. In filtration research a theoretical framework which incorporates all the important aspects of filtration process has been developed to quantitatively describe the dynamic behavior of the process.

In liquid phase adsorption studies, efficient algorithms are developed for exact and detailed adsorption calculations in various process configurations involving systems with arbitrarily large number of adsorbates, formulation of the species-grouping procedure for simplifying multicomponent adsorption calculations and establishment of a characterization procedure which describes gas solution with unknown adsorbates as solution with a fixed number of pseudo-species of adsorbates.

In biochemical engineering research, Tien's group is studying the interaction between adsorption and bacterial growth when granular activated carbon is used to treat liquid waste containing both adsorbable and biodegradable organic substrates. The work is applied to fluidized bed biofilm reactor design.

**Professor Vook** is studying various properties of current carrying and sliding electrical contacts. The work is carried out in an ultra high vacuum system where electrical contact resistance, friction coefficient, and the chemical composition of the slip ring surface (by Auger electron spectroscopy) are measured in situ as a function of contact force, current through the contact, and gaseous lubricating environment. The goal of this work is to understand the physical and chemical forces that limit the current-carrying capacity of the moving (rotating) electrical contact. Vook is also developing thin film coatings and surface pretreatments for preventing the out-of-core radioactive buildup that occurs on austenitic stainless steels used in boiling water nuclear reactors.

**Chiu-Sen Wang** is on leave for a few years and working at CalTech in the area of particle deposition in branched airways (e.g. the lungs), and in aerosols.

These projects illustrate the breadth and depth of the research interests of the faculty at Syracuse. There is breadth in the number and variety of research interests and depth in that several faculty members work in the key areas of separation and transport processes, chemical reaction engineering, fluid-particle technology, and materials science.  $\square$

# ***AUTHOR GUIDELINES***

This guide is offered to aid authors in preparing manuscripts for CHEMICAL ENGINEERING EDUCATION (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

CEE publishes papers in the broad field of chemical engineering education. Papers generally describe a course, a laboratory, a ChE department, a ChE educator, a ChE curriculum, research program, machine computation, special instructional programs or give views and opinions on various topics of interest to the profession.

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**TITLE.** Use specific and informative titles. They should be as brief as possible, consistent with the need for defining the subject area covered by the paper.

**AUTHORSHIP.** Be consistent in authorship designation. Use first name, second initial, and surname. Give complete mailing address of place where work was conducted. If current address is different, include it in the footnote on title page.

**TEXT.** Consult recent issues for general style. Assume your reader is not a novice in the field. Include only as much history as is needed to provide background for the particular material covered in your paper. Sectionalize the article and insert brief appropriate headings.

**TABLES.** Avoid tables and graphs which involve duplication or superfluous data. If you can use a graph, do not include a table. If the reader needs the table, omit the graph. Substitute a few typical results for lengthy tables when practical. Avoid computer printouts.

**NOMENCLATURE.** Follow nomenclature style of CHEMICAL ABSTRACTS; avoid trivial names. If trade names are used, define at point of first use. Trade names should carry an initial capital only, with no accompanying footnote. Use consistent units of measurement and give dimensions for all terms. Write all equations and formulas clearly, and number important equations consecutively.

**ACKNOWLEDGMENT.** Include in acknowledgment only such credits as are essential.

**LITERATURE CITED.** References should be numbered and listed on a separate sheet in order occurring in text.

**COPY REQUIREMENTS.** Send two legible copies of manuscript, typed (double-spaced) on 8½ X 11 inch paper. Clear duplicated copies are acceptable. Submit original drawings (or sharp prints) of graphs and diagrams, and clear glossy prints of photographs. Prepare original drawings on tracing paper or high quality paper; use black India ink and a lettering set. Choose graph papers with blue cross-sectional lines; other colors interfere with good reproduction. Label ordinates and abscissas of graphs along the axes and outside the graph proper. Figure captions and legends may be set in type and need not be lettered on the drawings. Number all illustrations consecutively. Supply all captions and legends typed on a separate page. If drawings are mailed under separate cover, identify by name of author and title of manuscript. State in cover letter if drawings or photographs are to be returned. Authors should include brief biographical sketches and recent photographs with the manuscript.

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